RP-Check: An Architecture for Spaceflight Command Sequence Validation

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Artist's Concept. NASA/JPL-Caltech

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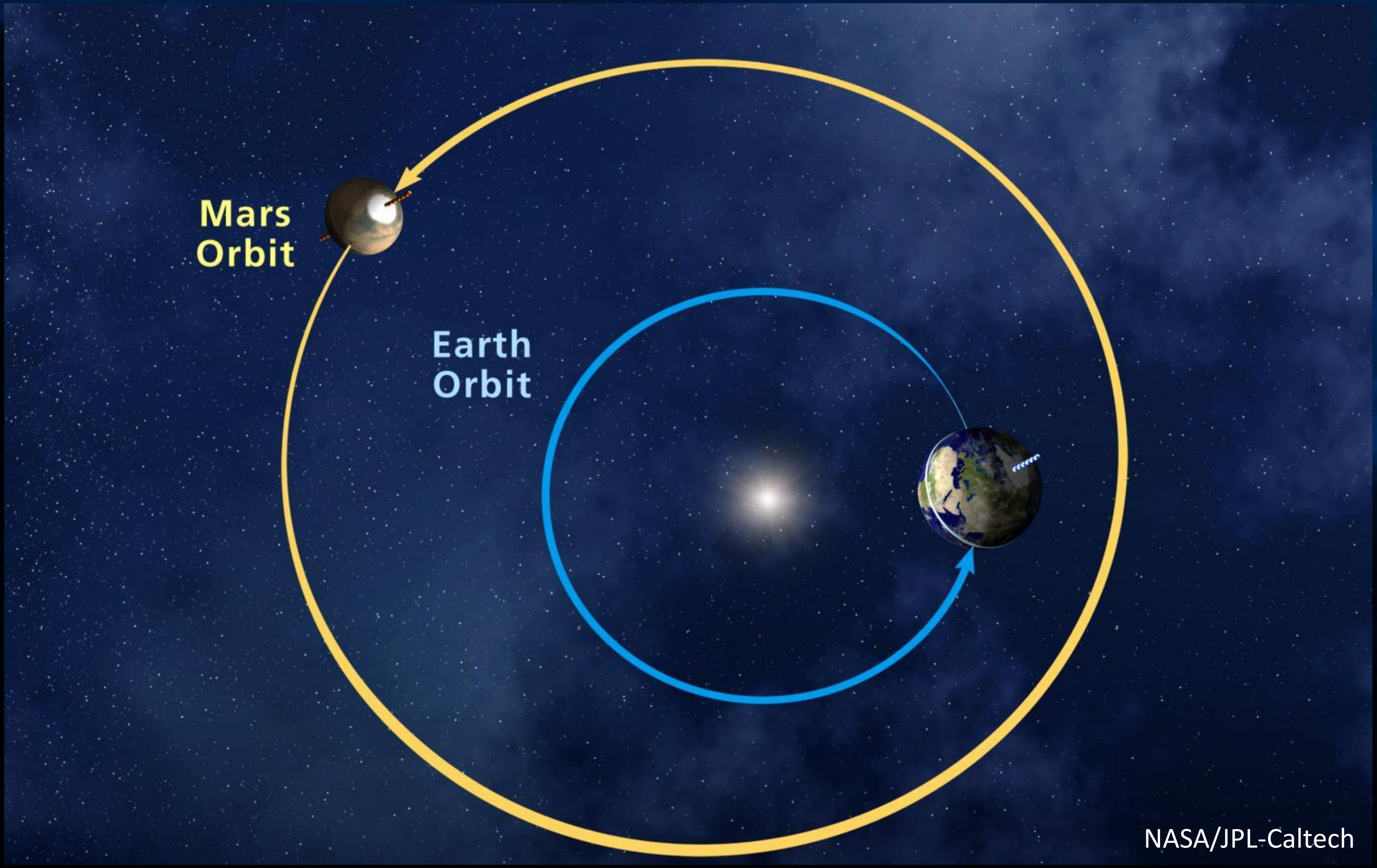
We can’t drive a rover in real time due to the distance between Earth and Mars.



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It takes between 4 and 22 minutes each way for a signal to travel between the two planets.

Also, Logistics

The Deep Space Network is a shared resource for dozens of missions.

We often only get one uplink and a few downlink windows each day

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Humans Plan Daily Rover Operations

Dozens of scientists and engineers support each day of planned mission operations.

Two or more *Rover Planners* are responsible for sequencing daily Mobility, Arm, and Turret Operations using RSVP tool.

RP-check was written to make Rover Planners aware of any conflicts with Flight Rules or Best Practices early enough in the day to allow time to re-plan.

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Flight Rules

- Flight Rules are English constraints on mission operations
  - Lessons learned while creating the spacecraft
  - Problems or idiosyncrasies discovered during mission operations.
- Enforced daily by manual review and via automated checkers (Seqgen, SSIM, *RP-check*)

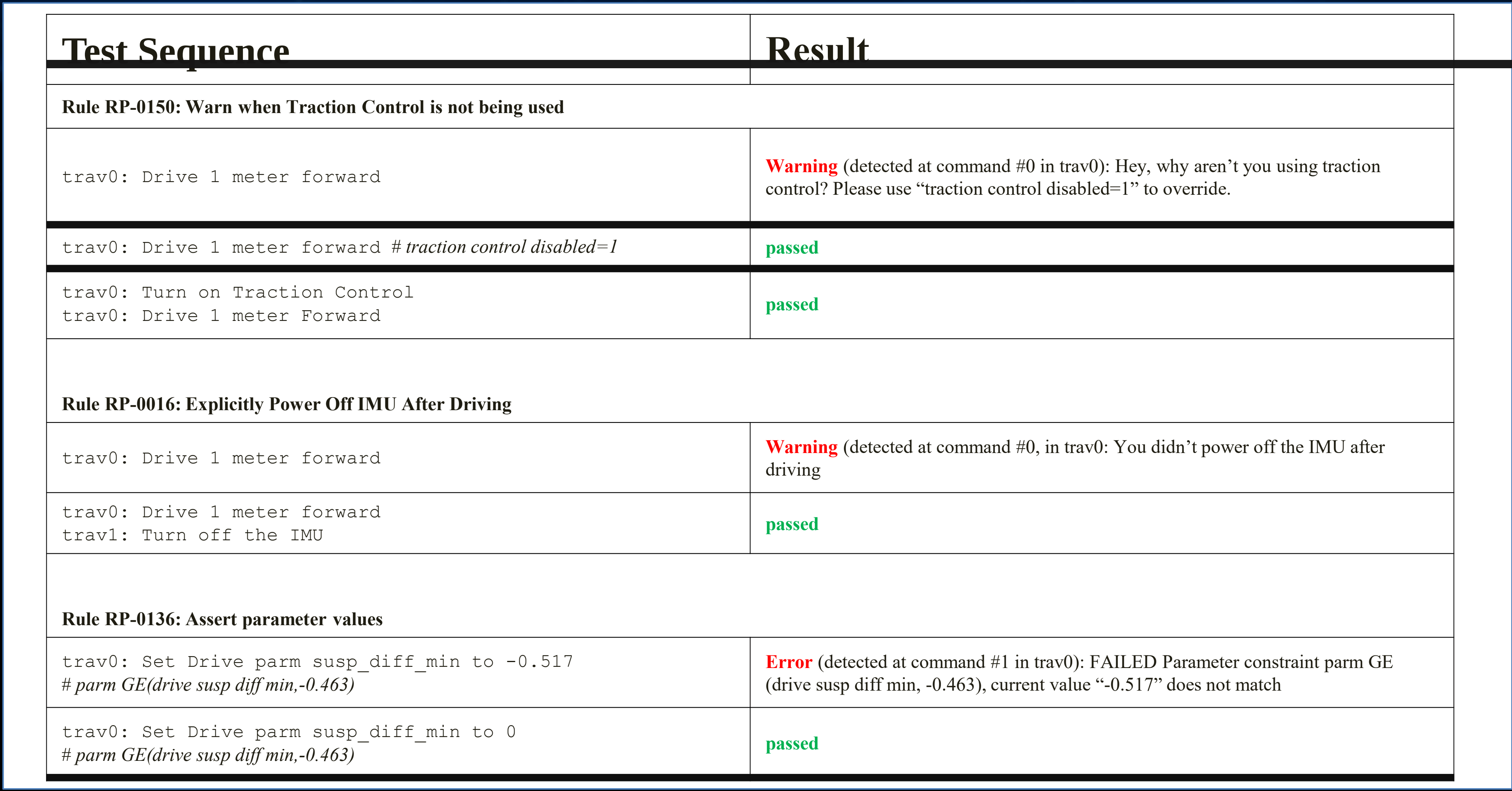
RP-check Processing

- Create Annotations of important state estimates
  - Motor positions, Vehicle position and attitude, cover status, 25,000 initial parameter values
  - Also queries near-term overall plan information to ensure Rover Planner commands are scheduled correctly
- Generate an Execution Trace containing all commands more-or-less in order
  - Nested command sequence calls are expanded
  - Includes both branches at conditionals
- Apply over 242 rule checks looking for violations
  - Link back to each command that caused a violation
  - These may be run in parallel on multicore processors

Model Fidelity

- RP-check keeps things simple
  - Mobility models only X,Y and Heading
  - Drill feed position models terrain location as simply “unknown”
- Rules model just what they need
  - Simple argument-checking rules need no model at all
- Implementation language is flexible
  - Supports both simple models and highly complex models (e.g. Visual Odometry frustum overlap computations); no arbitrary restrictions based on an assumed language.

Example Tests of Best Practice Rules



Test Sequence	Result
Rule RP-0150: Warn when Traction Control is not being used	
`trav0: Drive 1 meter forward`	**Warning** (detected at command #0 in trav0): Hey, why aren't you using traction control? Please use "traction control disabled=1" to override.
`trav0: Drive 1 meter forward` *# traction control disabled=1*	**passed**

`trav0: Turn on Traction Control`
`trav0: Drive 1 meter Forward`
	passed

Rule RP-0016: Explicitly Power Off IMU After Driving	
`trav0: Drive 1 meter forward`	**Warning** (detected at command #0, in trav0: You didn't power off the IMU after driving

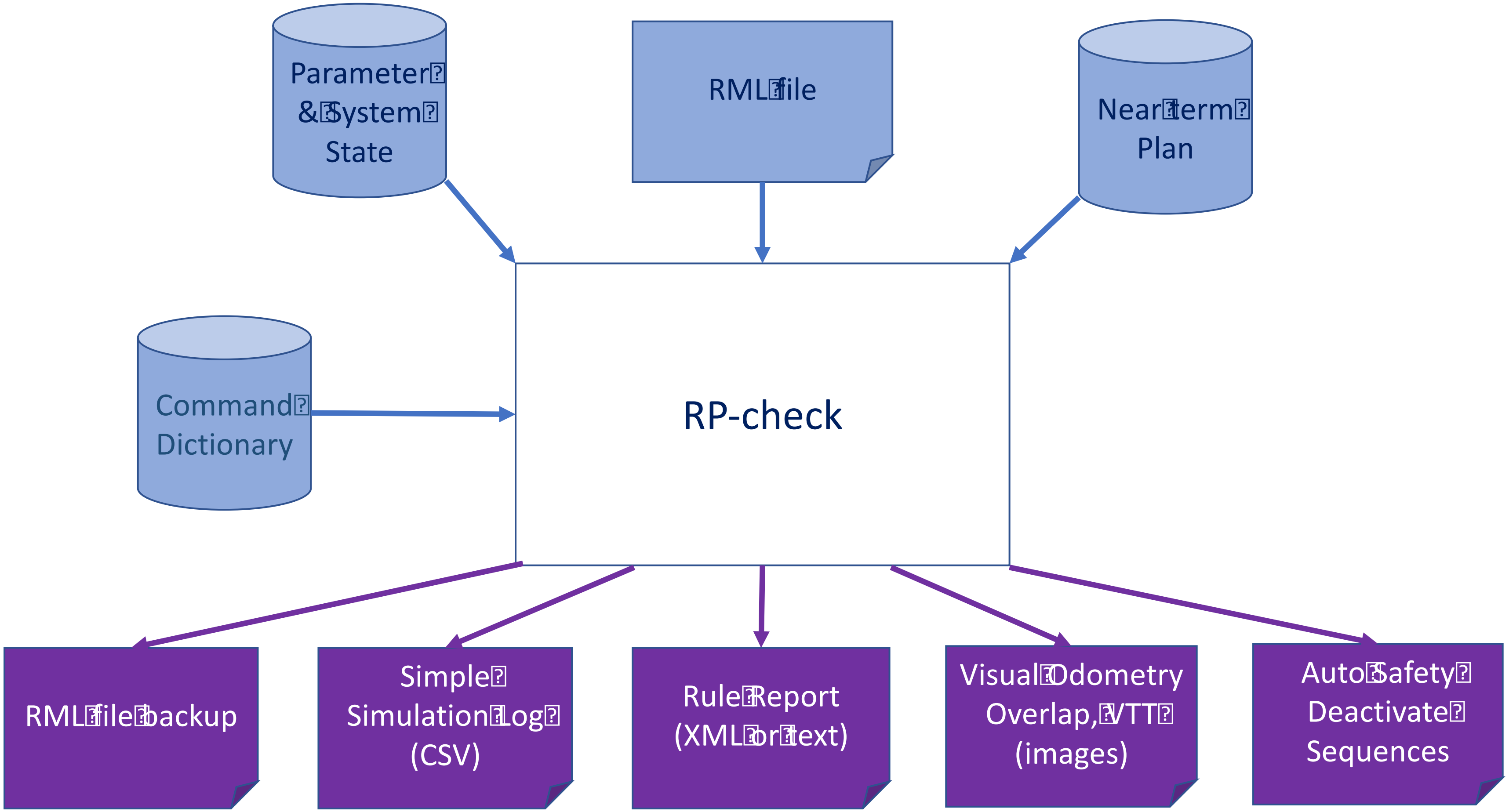
`trav0: Drive 1 meter forward`
`trav1: Turn off the IMU`
	passed

Rule RP-0136: Assert parameter values	
`trav0: Set Drive parm susp_diff_min to -0.517` *# parm GE(drive susp diff min,-0.463)*	**Error** (detected at command #1 in trav0): FAILED Parameter constraint parm GE (drive susp diff min, -0.463), current value "-0.517" does not match
`trav0: Set Drive parm susp_diff_min to 0` *# parm GE(drive susp diff min,-0.463)*	**passed**

- Regression test suite includes over 1,000 such tests

RP-check Inputs and Outputs

Rover Markup Language (RML) files hold command sequences



Parameter & System State

RML file

Near term Plan

Command Dictionary

RP-check

RML file backup

Simple Simulation Log (CSV)

Rule Report (XML or text)

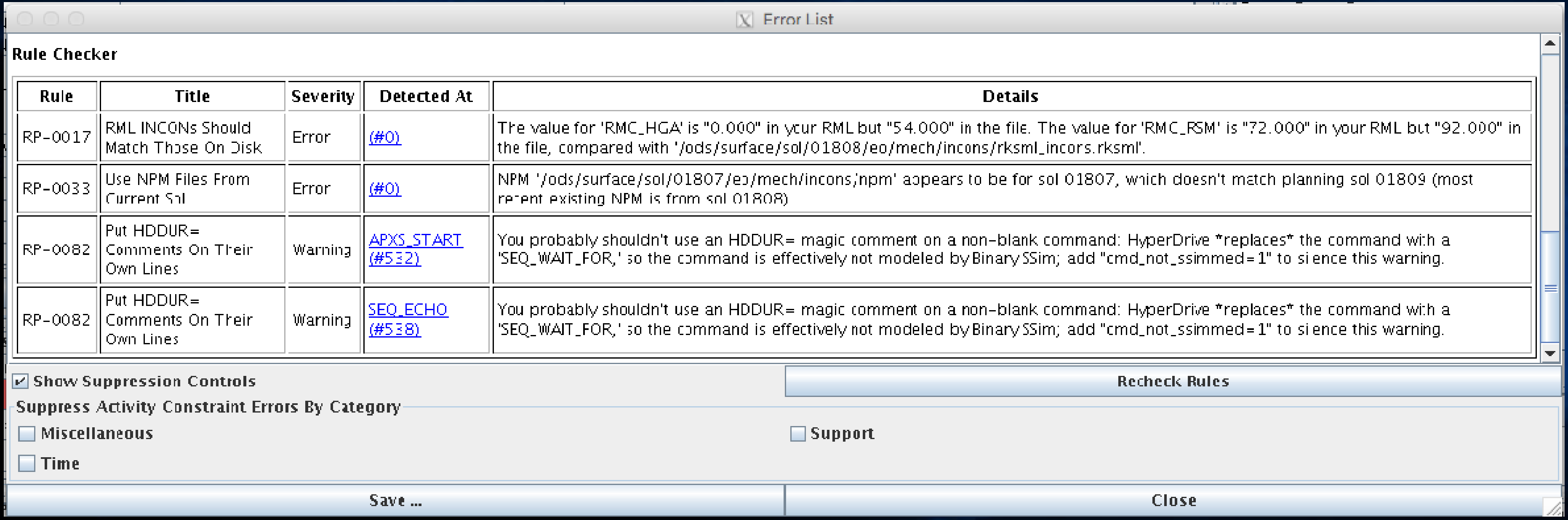
Visual Odometry Overlap, VTT (images)

Auto Safety Deactivate Sequences

Reports Generated

- Backup: Saves a copy of its input RML file
- Simulation Log: CSV file showing the simulated Mobility Annotations used in rule evaluations
- Rule Violations Report: XML or text report documenting each rule violation, with links back to exactly what command prompted each warning
- Visual Odometry / Visual Tracking Reports: Image-annotated report documenting the assessment made of image tracking capabilities, useful in interpreting any warnings
- Auto Safety Deactivate Sequences: auto-generated commands to gracefully recover from too-long sequence backbone execution

Rule Violations Report



Rule Checker

Rule	Title	Severity	Detected At	Details
RP-0017	RML INCONs Should Match Those On Disk	Error	(#0)	The value for 'RMC_HGA' is "0.000" in your RML but "54.000" in the file. The value for 'RMC_RSM' is "72.000" in your RML but "92.000" in the file, compared with '/ods/surface/sol/01808/eo/mech/incons/rksml_incons.rksml'.
RP-0033	Use NPM Files From Current Sol	Error	(#0)	NPM '/ods/surface/sol/01807/eo/mech/incons/npm' appears to be for sol 01807, which doesn't match planning sol 01809 (most recent existing NPM is from sol 01808)
RP-0082	Put HDDUR= Comments On Their Own Lines	Warning	APXS_START (#532)	You probably shouldn't use an HDDUR= magic comment on a non-blank command: HyperDrive *replaces* the command with a 'SEQ_WAIT_FOR,' so the command is effectively not modeled by BinarySSim; add "cmd_not_ssimmed=1" to silence this warning.
RP-0082	Put HDDUR= Comments On Their Own Lines	Warning	SEQ_ECHO (#538)	You probably shouldn't use an HDDUR= magic comment on a non-blank command: HyperDrive *replaces* the command with a 'SEQ_WAIT_FOR,' so the command is effectively not modeled by BinarySSim; add "cmd_not_ssimmed=1" to silence this warning.

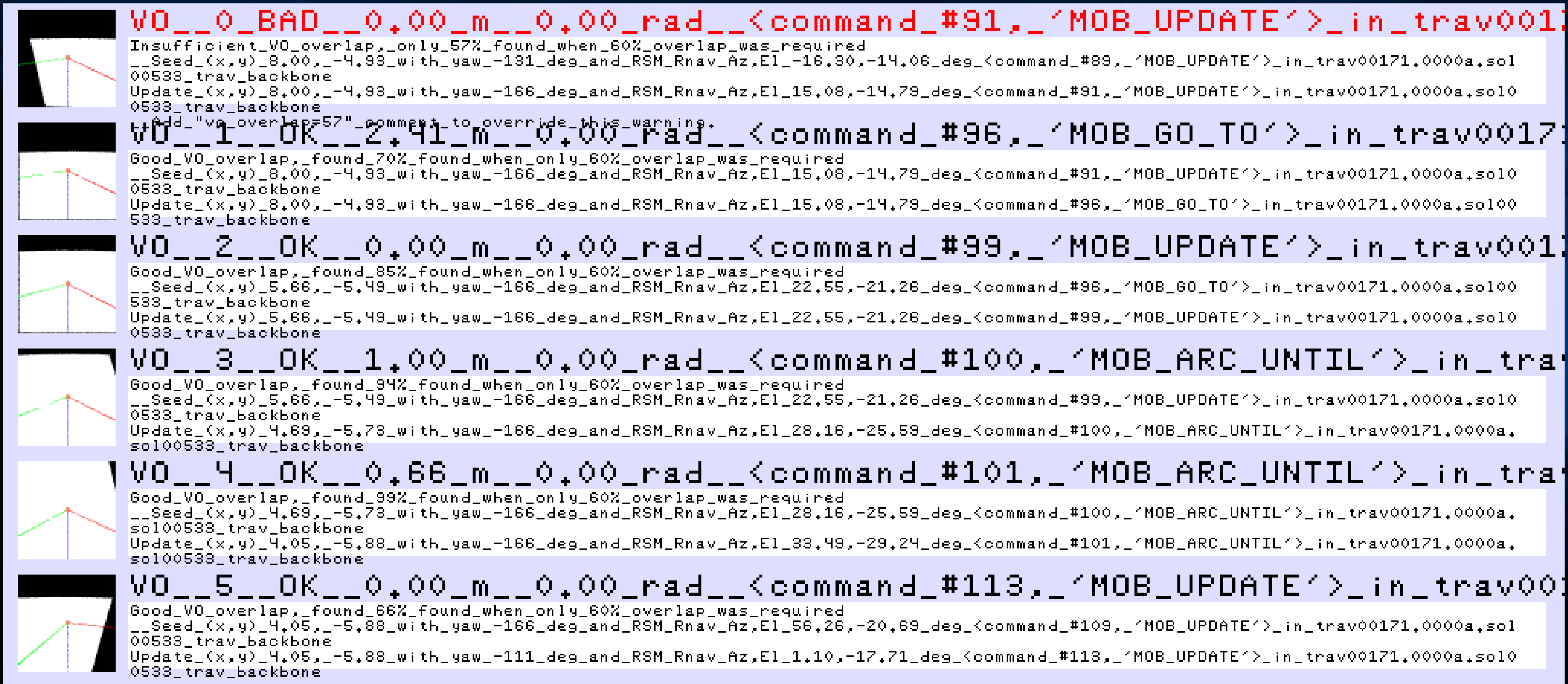
☑ Show Suppression Controls

Suppress Activity Constraint Errors By Category

☐ Miscellaneous ☐ Support

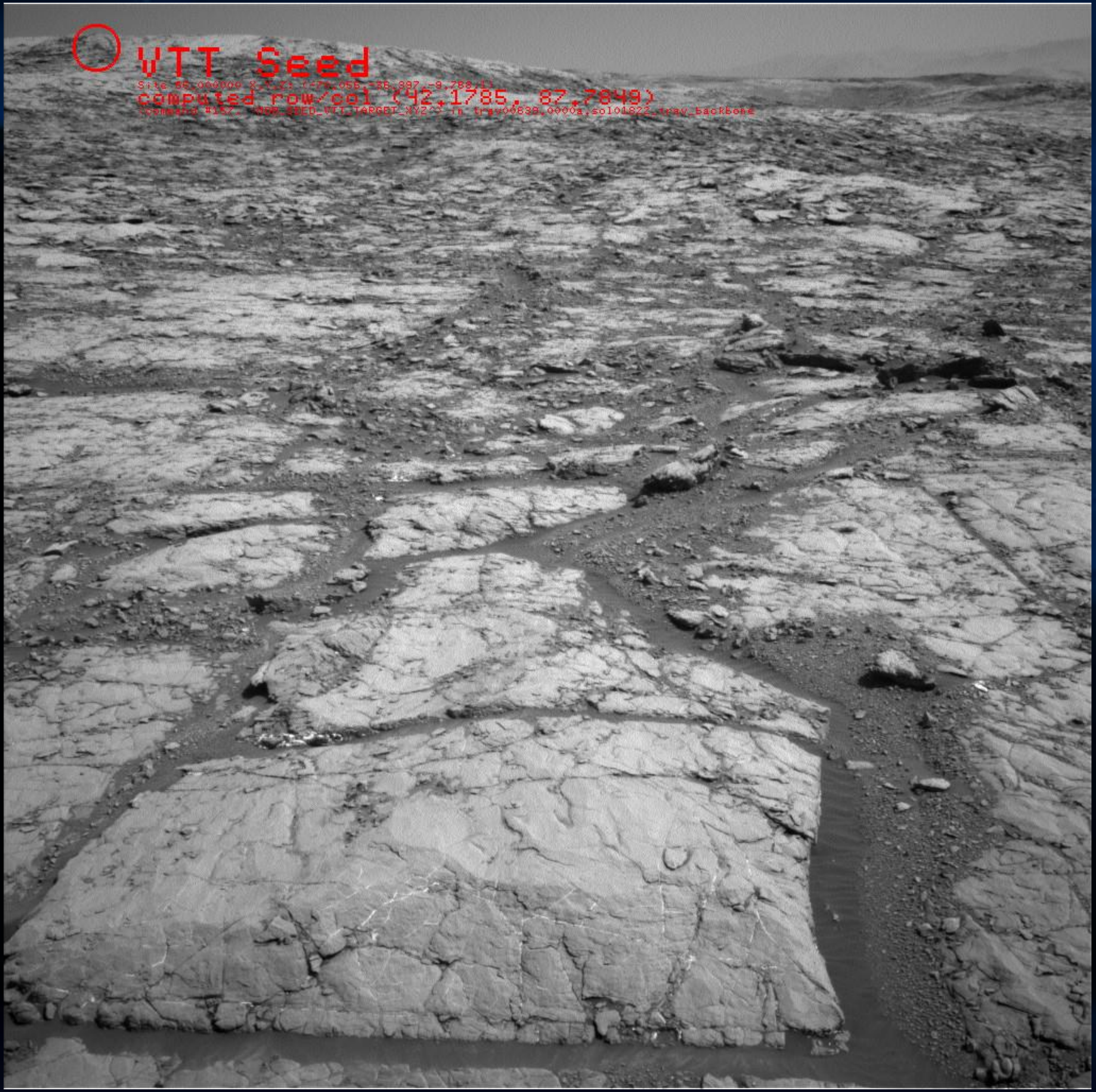
☐ Time

Visual Odometry Report



```
VO__0_BAD__0,00_m__0,00_rad__<command_#91,_´MOB_UPDATE´>_in_trav001
Insufficient_VO_overlap,_only_57%_found_when_60%_overlap_was_required
__Seed_(x,y)_8,00,_-4,93_with_yaw_-131_deg_and_RSM_Rnav_Az,El_-16,30,-14,06_deg_<command_#89,_´MOB_UPDATE´>_in_trav00171,0000a,sol
00533_trav_backbone
Update_(x,y)_8,00,_-4,93_with_yaw_-166_deg_and_RSM_Rnav_Az,El_15,08,-14,79_deg_<command_#91,_´MOB_UPDATE´>_in_trav00171,0000a,sol0
0533_trav_backbone
__Add_"vo_overlap=57"_comment_to_override_this_warning.
VO__1__OK__2,41_m__0,00_rad__<command_#96,_´MOB_GO_TO´>_in_trav0017
Good_VO_overlap,_found_70%_found_when_only_60%_overlap_was_required
__Seed_(x,y)_8,00,_-4,93_with_yaw_-166_deg_and_RSM_Rnav_Az,El_15,08,-14,79_deg_<command_#91,_´MOB_UPDATE´>_in_trav00171,0000a,sol0
0533_trav_backbone
Update_(x,y)_8,00,_-4,93_with_yaw_-166_deg_and_RSM_Rnav_Az,El_15,08,-14,79_deg_<command_#96,_´MOB_GO_TO´>_in_trav00171,0000a,sol00
533_trav_backbone
VO__2__OK__0,00_m__0,00_rad__<command_#99,_´MOB_UPDATE´>_in_trav001
Good_VO_overlap,_found_85%_found_when_only_60%_overlap_was_required
__Seed_(x,y)_5,66,_-5,49_with_yaw_-166_deg_and_RSM_Rnav_Az,El_22,55,-21,26_deg_<command_#96,_´MOB_GO_TO´>_in_trav00171,0000a,sol00
533_trav_backbone
Update_(x,y)_5,66,_-5,49_with_yaw_-166_deg_and_RSM_Rnav_Az,El_22,55,-21,26_deg_<command_#99,_´MOB_UPDATE´>_in_trav00171,0000a,sol0
0533_trav_backbone
VO__3__OK__1,00_m__0,00_rad__<command_#100,_´MOB_ARC_UNTIL´>_in_tra
Good_VO_overlap,_found_94%_found_when_only_60%_overlap_was_required
__Seed_(x,y)_5,66,_-5,49_with_yaw_-166_deg_and_RSM_Rnav_Az,El_22,55,-21,26_deg_<command_#99,_´MOB_UPDATE´>_in_trav00171,0000a,sol0
0533_trav_backbone
Update_(x,y)_4,69,_-5,73_with_yaw_-166_deg_and_RSM_Rnav_Az,El_28,16,-25,59_deg_<command_#100,_´MOB_ARC_UNTIL´>_in_trav00171,0000a,
sol00533_trav_backbone
VO__4__OK__0,66_m__0,00_rad__<command_#101,_´MOB_ARC_UNTIL´>_in_tra
Good_VO_overlap,_found_99%_found_when_only_60%_overlap_was_required
__Seed_(x,y)_4,69,_-5,73_with_yaw_-166_deg_and_RSM_Rnav_Az,El_28,16,-25,59_deg_<command_#100,_´MOB_ARC_UNTIL´>_in_trav00171,0000a,
sol00533_trav_backbone
Update_(x,y)_4,05,_-5,88_with_yaw_-166_deg_and_RSM_Rnav_Az,El_33,49,-29,24_deg_<command_#101,_´MOB_ARC_UNTIL´>_in_trav00171,0000a,
sol00533_trav_backbone
VO__5__OK__0,00_m__0,00_rad__<command_#113,_´MOB_UPDATE´>_in_trav00
Good_VO_overlap,_found_66%_found_when_only_60%_overlap_was_required
__Seed_(x,y)_4,05,_-5,88_with_yaw_-166_deg_and_RSM_Rnav_Az,El_56,26,-20,69_deg_<command_#109,_´MOB_UPDATE´>_in_trav00171,0000a,sol
00533_trav_backbone
Update_(x,y)_4,05,_-5,88_with_yaw_-111_deg_and_RSM_Rnav_Az,El_1,10,-17,71_deg_<command_#113,_´MOB_UPDATE´>_in_trav00171,0000a,sol0
0533_trav_backbone
```

Visual Target Tracking Report


VTT Seed
Site 65.000000 X,Y,Z: (-70.056,-36.387,-9.788,1)
computed row/col (42.1785, 87.7849)
(command #157, MOB_SEED_VTT_TARGET_XYZ^^ in trav00838.0000a,sol01822_trav_backbone

Important Architectural Choices

- Speedy: RP-check completes in tens of seconds (vs. tens of minutes for other tools)
- 100% coverage: Evaluates all commands, including off-nominal
- Few false positives: Keep users focused
- Builtin Tool: Built into the RSVP/RoSE GUI editor
- Extensible: Easy to add rules and tests quickly
- Regression tests: can run through over a thousand test cases in under 10 minutes, can validate over a thousand flight plans against earlier releases.
- Expert Developers: RP-check has always been maintained within the Rover Planner team (FSW and Ground tool developers), allowing each rule to be written at an appropriate level of abstraction.

Tidbits

- Magic comments: Dozens of comments can communicate extra meaning to RP-check
  - Target=*Name*
  - parm_eq(*parameter*,*value*)
- Unit tests: Each unit test validates a single instance of a single rule
  - Easy to create specific test cases without worrying about violating other rules
- Self-training: RP-check helps train new Rover Planners

Flight Usage

- As of September 2017, the MSL version of RP-check:
  - has been in use in some form since 2004 (14 years)
  - Has 242 explicit rules (Flight Rules and RP-best practice)
  - Can generate 534 distinct warnings, 542 errors
  - Has evaluated 1,114 RML plans that have been sent to Mars on 1,139 different Sols
  - Has auto-generated Safety Deactivate sequences for a year
  - Is constantly being improved by the addition of new Best Practice and Flight Rule recommendations with fast turnaround.

Sample Flight Problem Resolutions

- Master Sol Check
  - Then: Sol 1247 had the wrong Master sequence name
  - Now: Reads the precise handover time form the plan to match Master sequence name
- Counting Motions between Visual Odometry Updates
  - Then: FSW bug discovered that led to inefficient imaging
  - Now: Avoided costly FSW update by modeling behavior
- Traction Control is Running
  - Then: Sol 1646 added new FSW to reduce wheel wear [see Friday talk!]
  - Now: Ensures the new capability is enabled

Conclusion

- Static analysis of spacecraft command sequences' conformity to mission Flight Rules and Rover Planner team best practices helps ensure operational safety
- The ability to quickly deploy new rules developed by experts keeps spacecraft operations safe and effective.
- Future missions might benefit from similar choices

BACKUP

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Robotics Tech used for Rovers

Visual Odometry, Slip Checks, VO Auto
Dense Stereo Vision
Autonomous Terrain Assessment
AutoNav and Guarded Driving
Local and Global Waypoint Planning
Multi-sol Driving
Visual Target Tracking
Simulation
Rover Sequencing and Visualization
Terrain Classification
Autonomous Image Interpretation for Science
Autonomous Fault Response
Velocity-controlled Driving
Precision Arm Placement
Percussive Drill
Cached Sample Manipulation
…

Curiosity Lets Human Drivers Choose the Level of Autonomy on Each Drive

Opportunity Sols 188-191
Rover 0 Wheel Odometry
Rover 1 Visodom Corrected
RSVP

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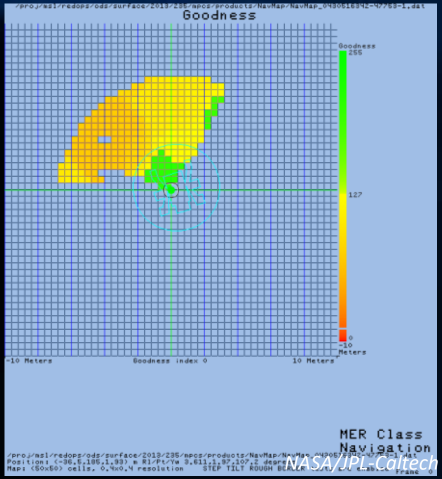
Visual odometry, or Slip Check + “Auto”



/proj/msl/redops/ods/surface/2013/235/mpcs/products/NavMap/NavMap_0430616342-47753-1.dat
Position: (-36.5,185.1,1.93) m Rl/Pt/Yw 3.611,1.87,107.2 degrees
Map: (50x50) cells, 0.4x0.4 resolution STEP TILT ROUGH BORDER tests are enabled

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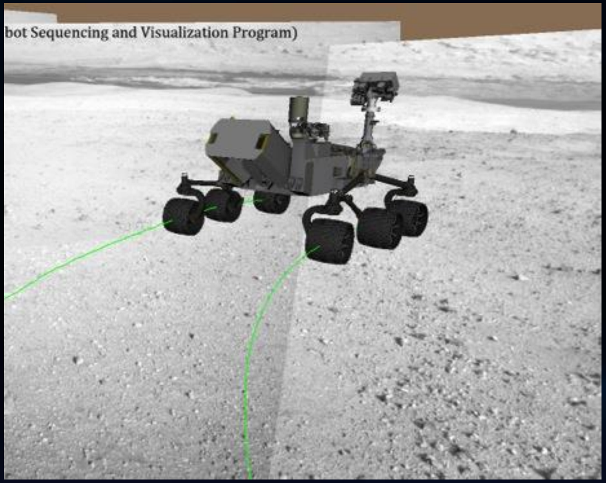
Auto-navigation; Geometric Hazard Detection and Avoidance

Visual Target Tracking



Directed driving

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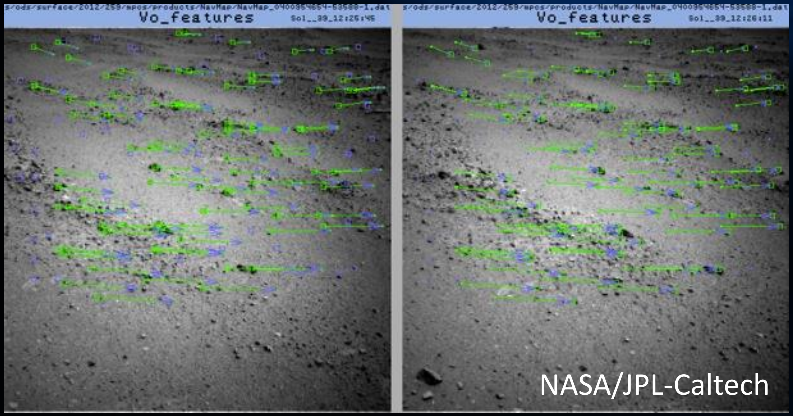
Using visual odometry, the rover constantly compares pairs of images of nearby terrain to calculate its position.


s/ods/surface/2012/259/mpos/products/NavMap/NavMap_0400964654-53588-1.dat
Vo_features
Sol__39_12:25:45
s/ods/surface/2012/259/mpos/products/NavMap/NavMap_0400964654-53588-1.dat
Vo_features
Sol__39_12:26:11

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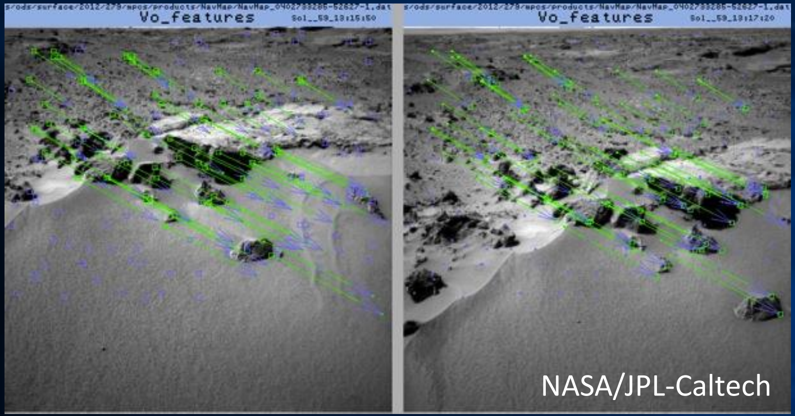
s/ods/surface/2012/279/mpos/products/NavMap/NavMap_0402789285-52627-1.dat
Vo_features
Sol__59_13:15:50
s/ods/surface/2012/279/mpos/products/NavMap/NavMap_0402789285-52627-1.dat
Vo_features
Sol__59_13:17:20

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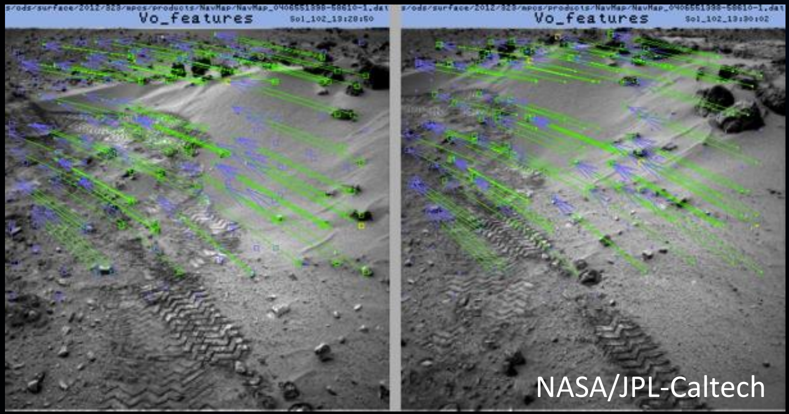
s/ods/surface/2012/323/mpos/products/NavMap/NavMap_0406551398-58610-1.dat
Vo_features
Sol_102_13:28:50
s/ods/surface/2012/323/mpos/products/NavMap/NavMap_0406551398-58610-1.dat
Vo_features
Sol_102_13:30:02

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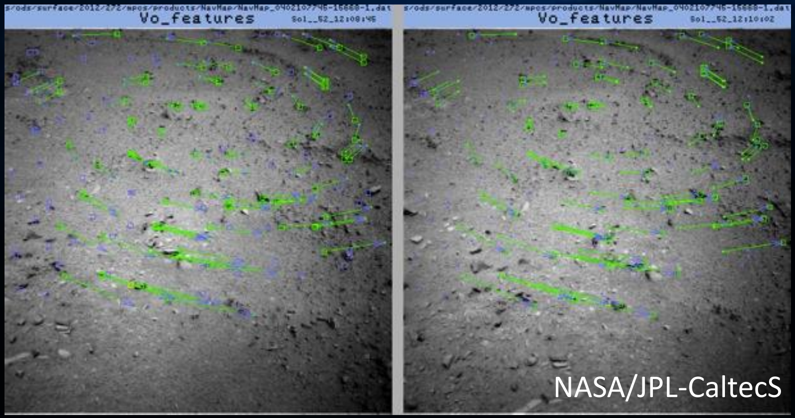
s/ods/surface/2012/272/mpos/products/NavMap/NavMap_0402107746-15668-1.dat
Vo_features
Sol__52_12:08:45
s/ods/surface/2012/272/mpos/products/NavMap/NavMap_0402107746-15668-1.dat
Vo_features
Sol__52_12:10:02

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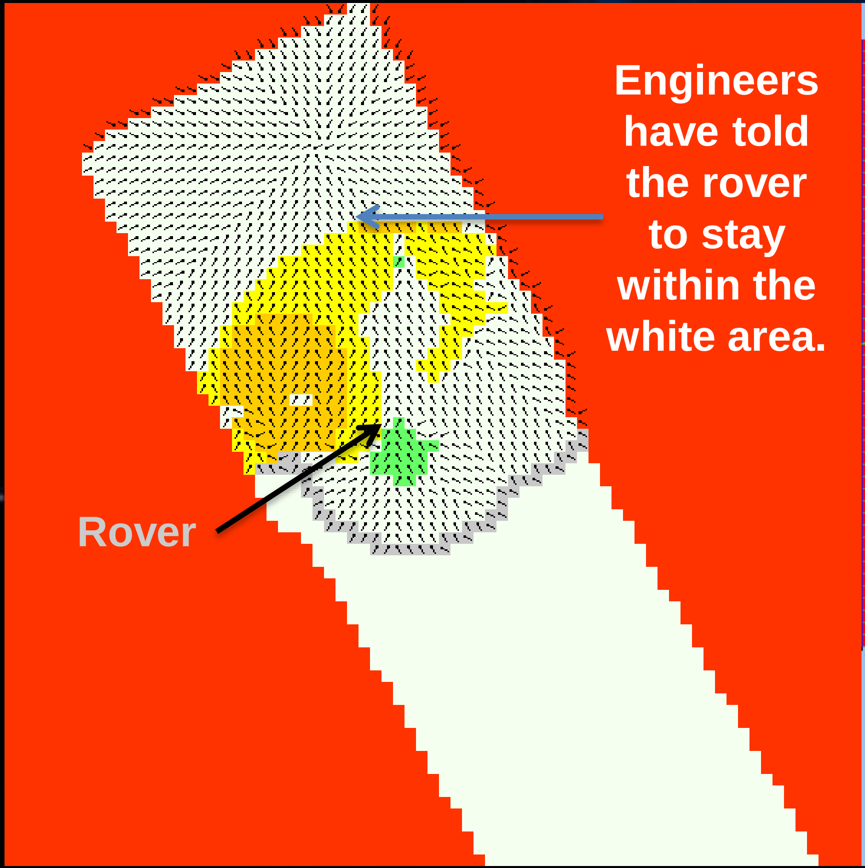
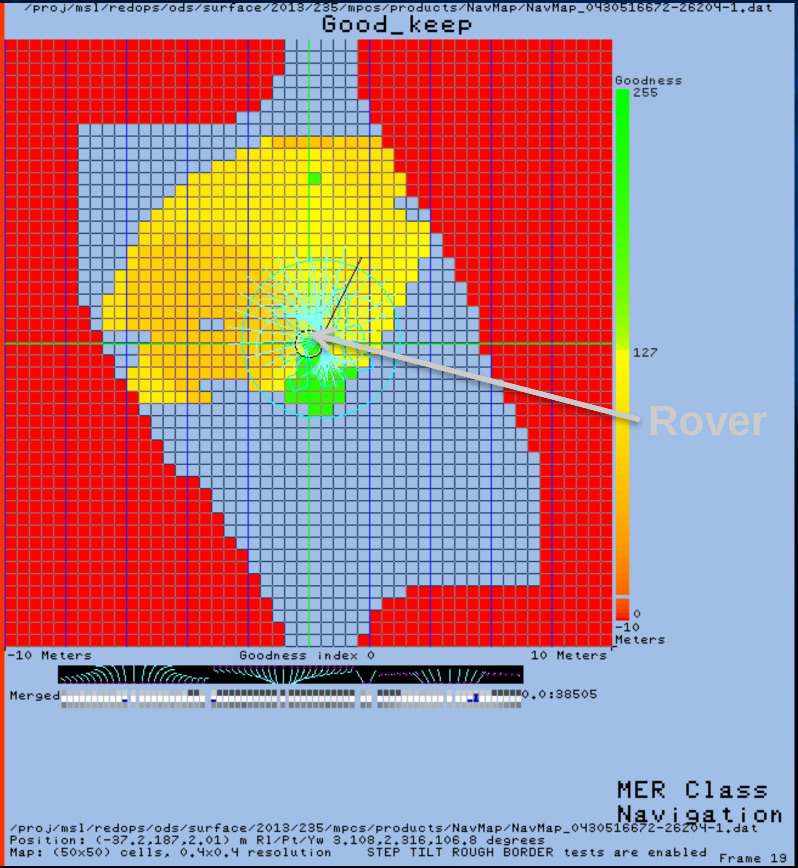
Unlike terrestrial robots, Curiosity drives as far as possible between VO images

NASA/JPL-Caltech

The rover reduces a stereo point cloud into a configuration space, labeling unsafe areas red and safe areas green.



Engineers have told the rover to stay within the white area.



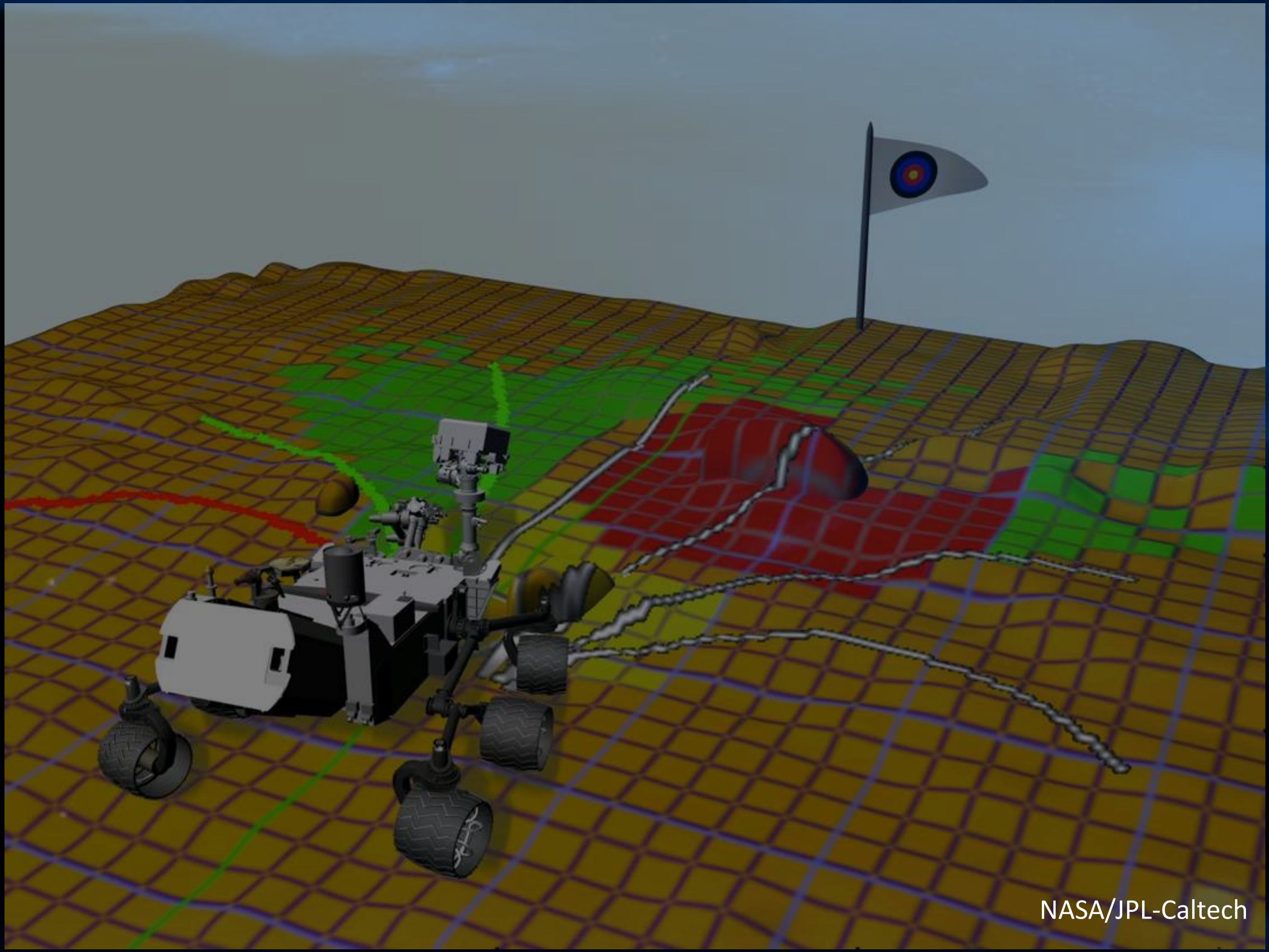
```
/proj/msl/redops/ods/surface/2013/235/mpcs/products/NavMap/NavMap_0430516672-26204-1.dat
```

```
/proj/msl/redops/ods/surface/2013/235/mpcs/products/NavMap/NavMap_0430516672-26204-1.dat
Position: (-37.2,187.2.01) m Rl/Pt/Yw 3.108,2.316,106.8 degrees
Map: (50x50) cells, 0.4x0.4 resolution    STEP TILT ROUGH BORDER tests are enabled
```

NASA/JPL-Caltech

Yellow means drive carefully, just like on Earth.

Watch “Rover Navigation 101” online for deets.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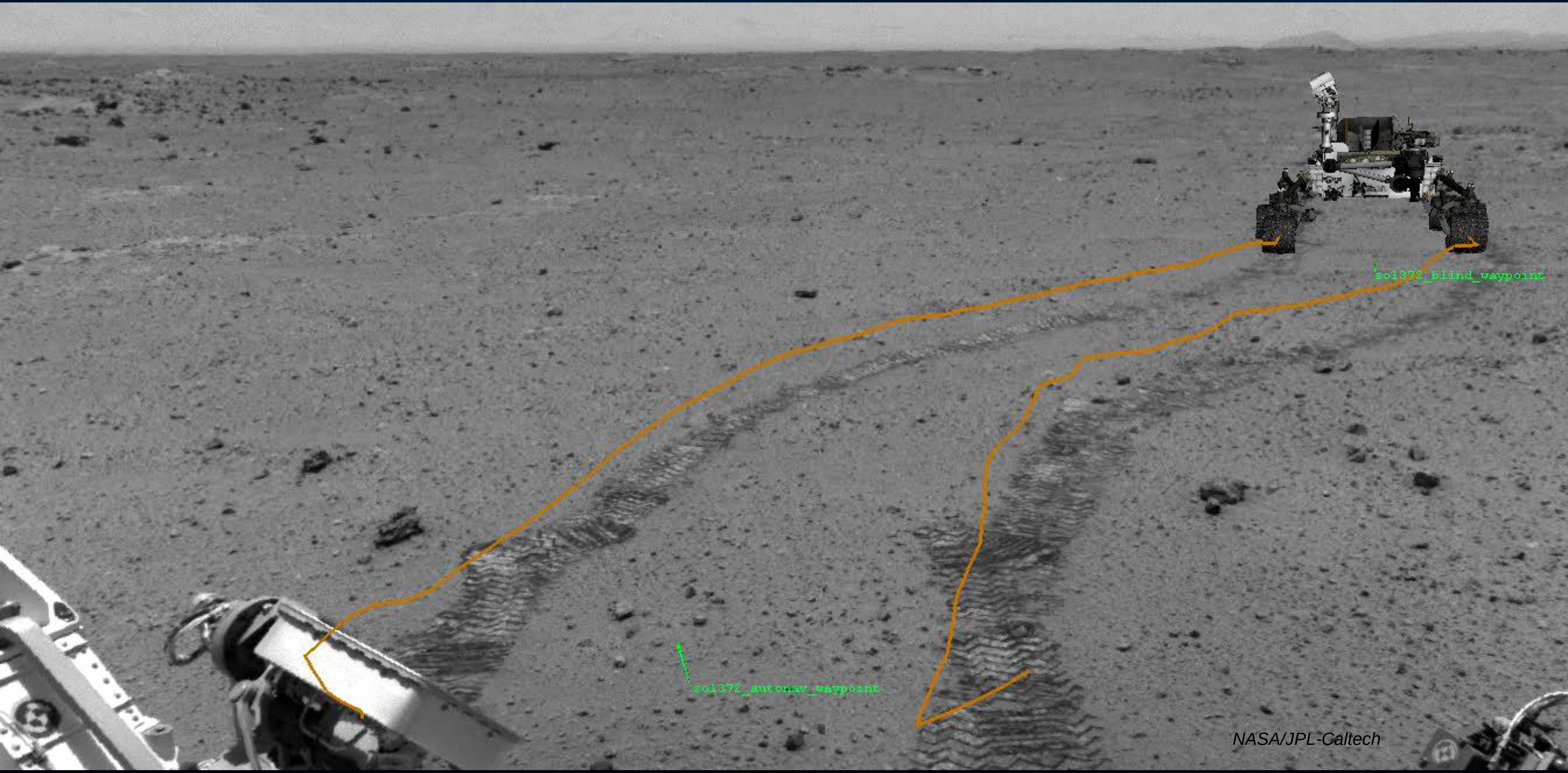
Animation of Curiosity’s actual Sol 372 drive over a picture of her tracks



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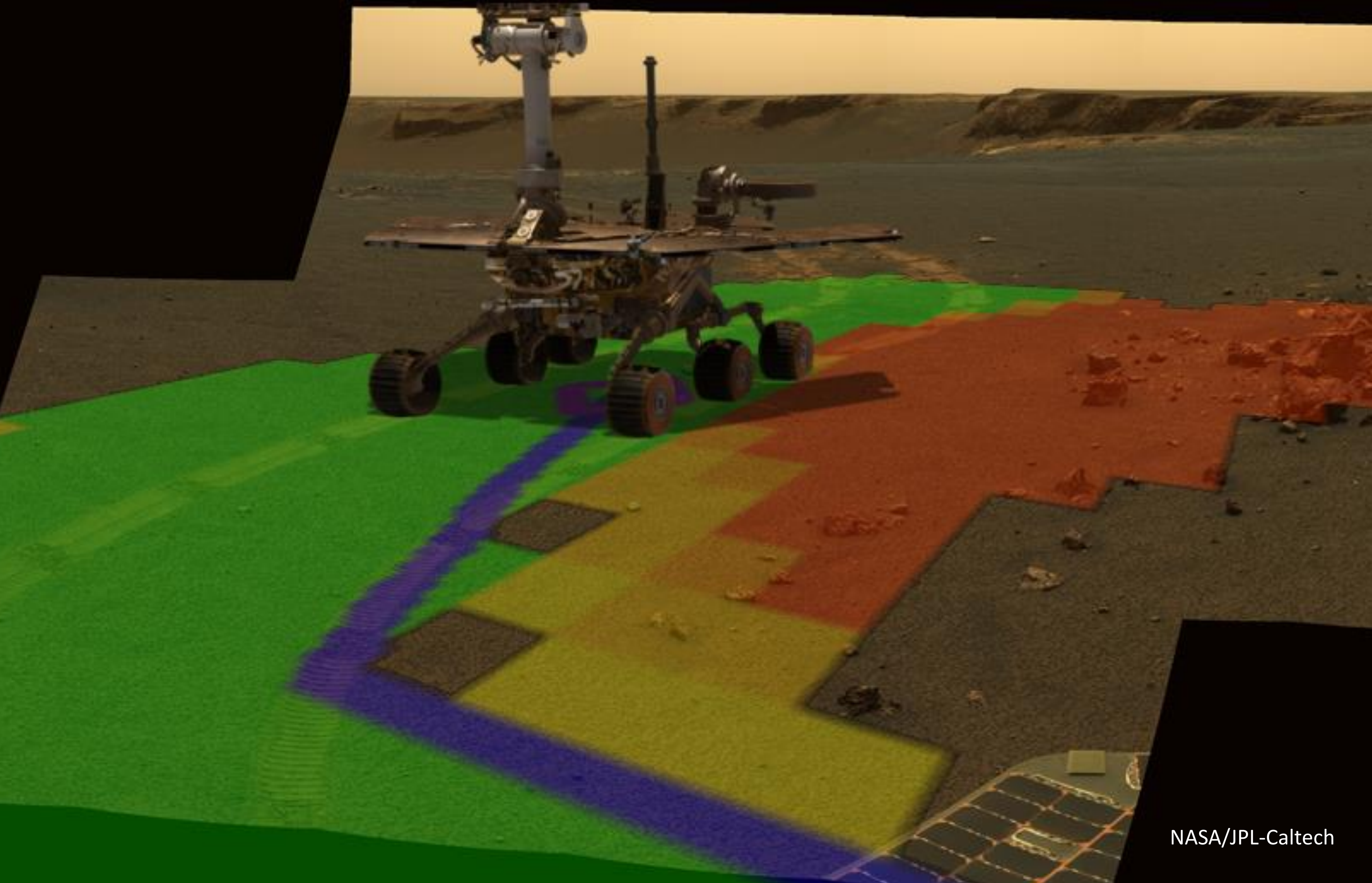
Finish!

D* Global Planner on Opportunity



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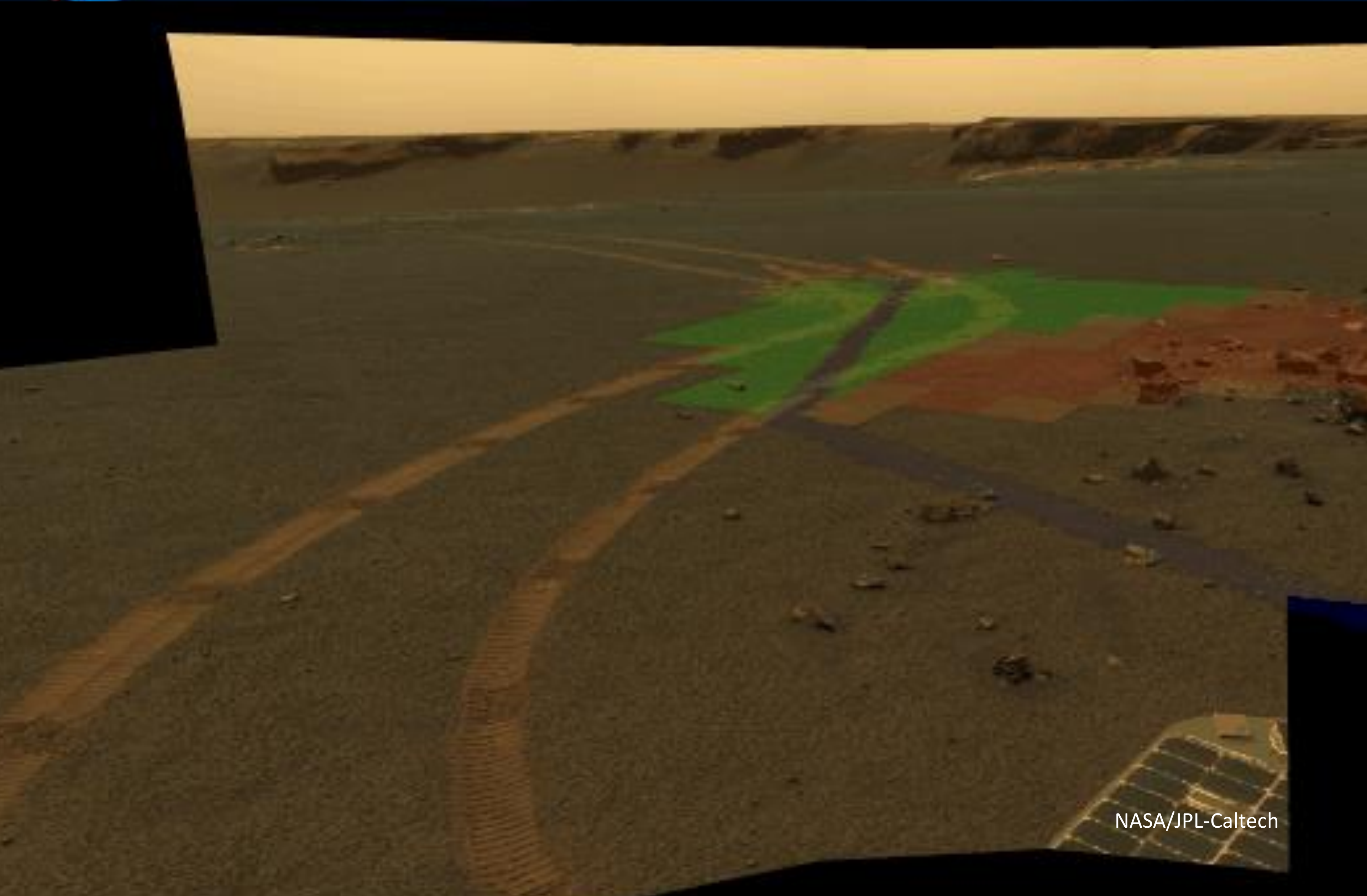
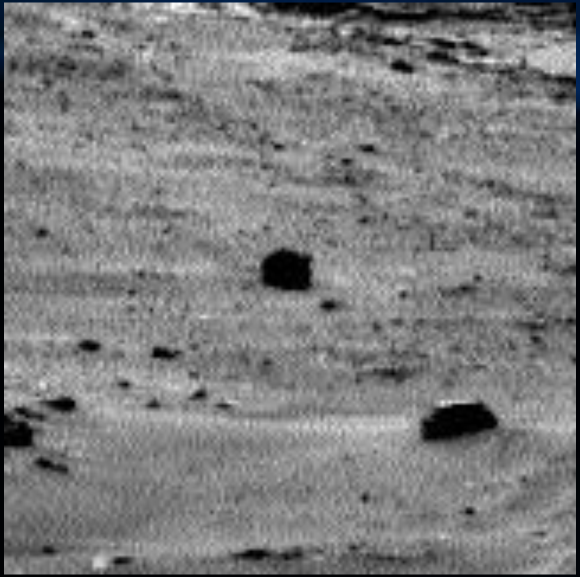
D* Global Planner on Opportunity

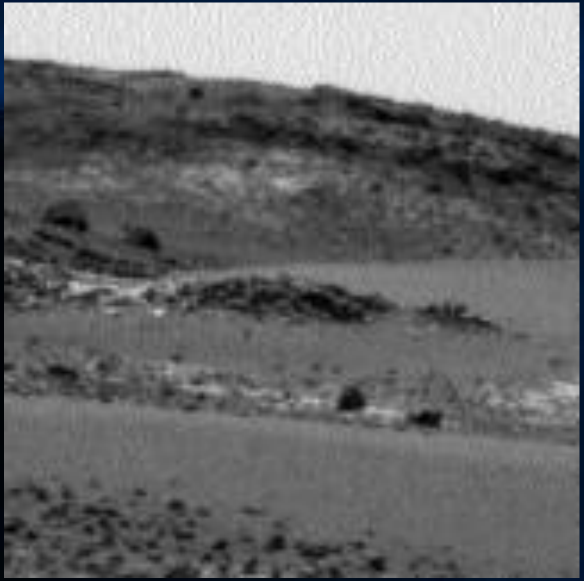


NASA/JPL-Caltech

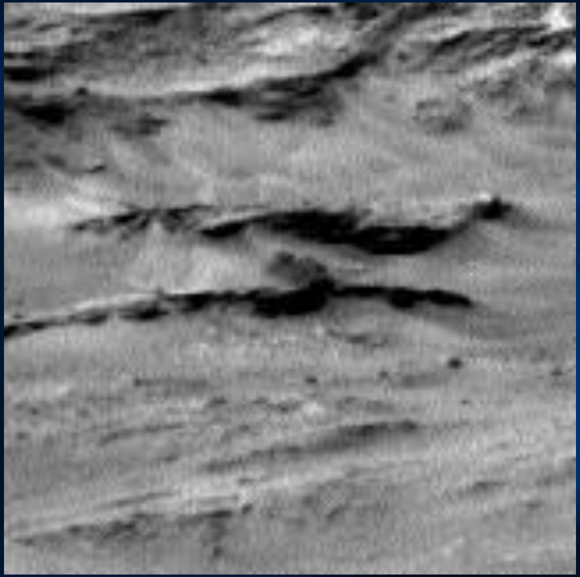
Visual Target Tracking



Sol 743



Sol 923



Sol 967

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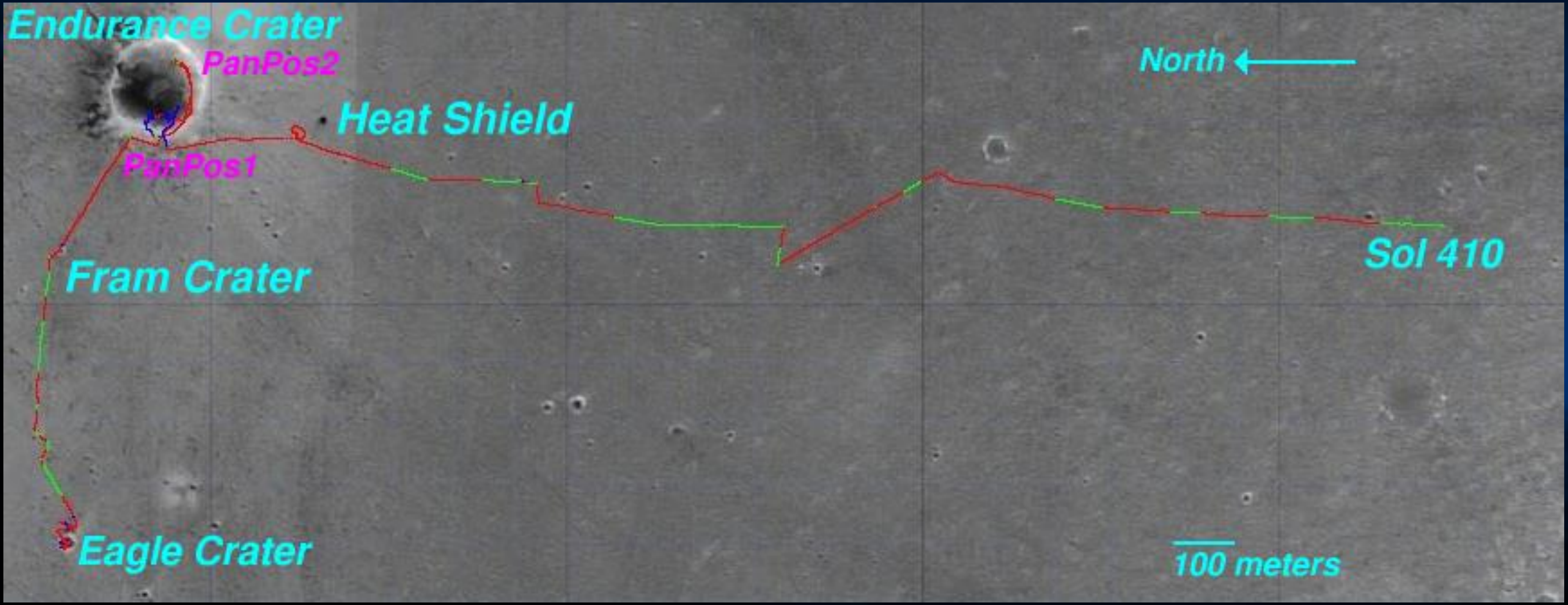
Opportunity Drives through Sol 410



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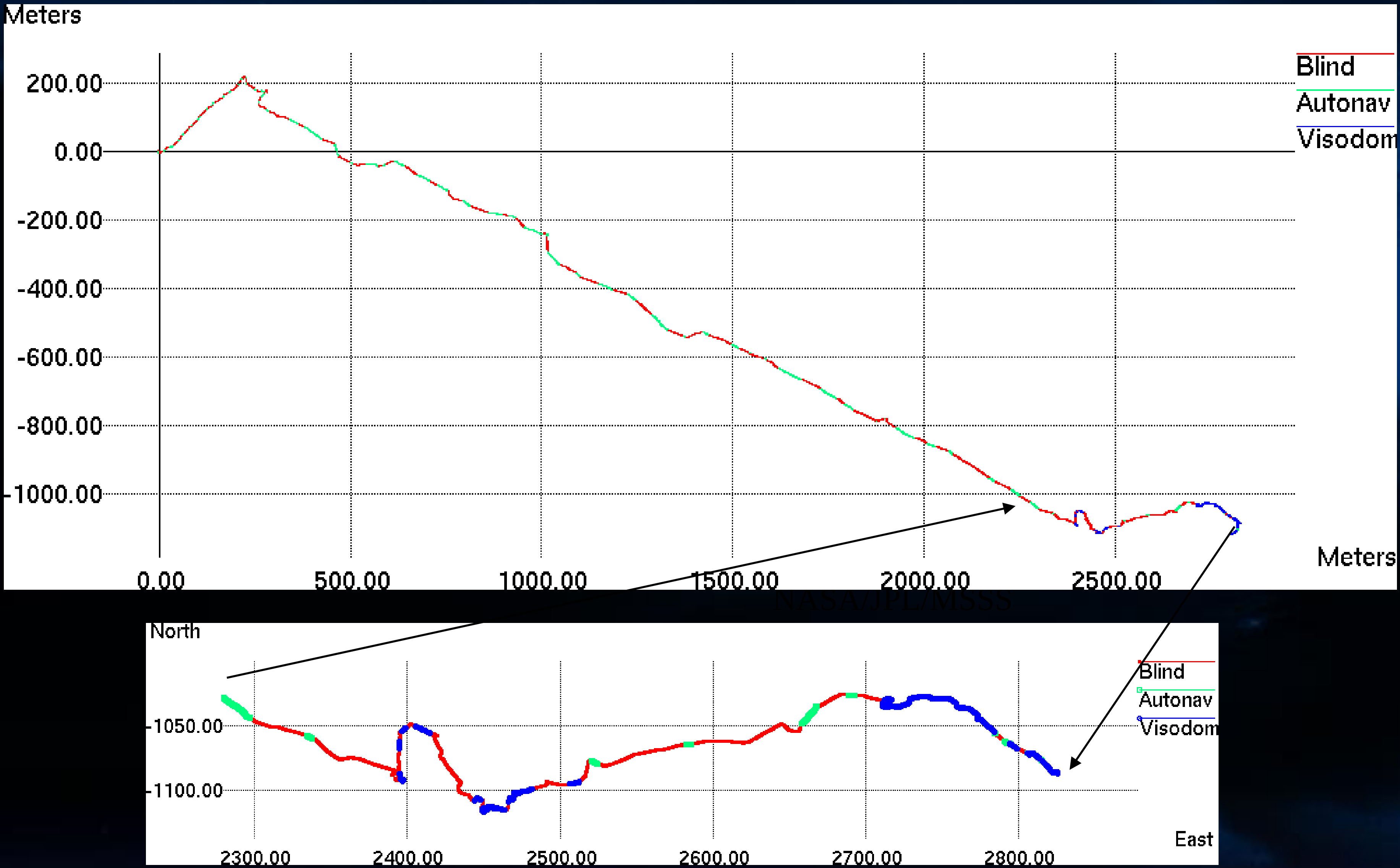
Driving Modes:

Blind

Autonav

Visodom

Spirit Drives through Sol 418



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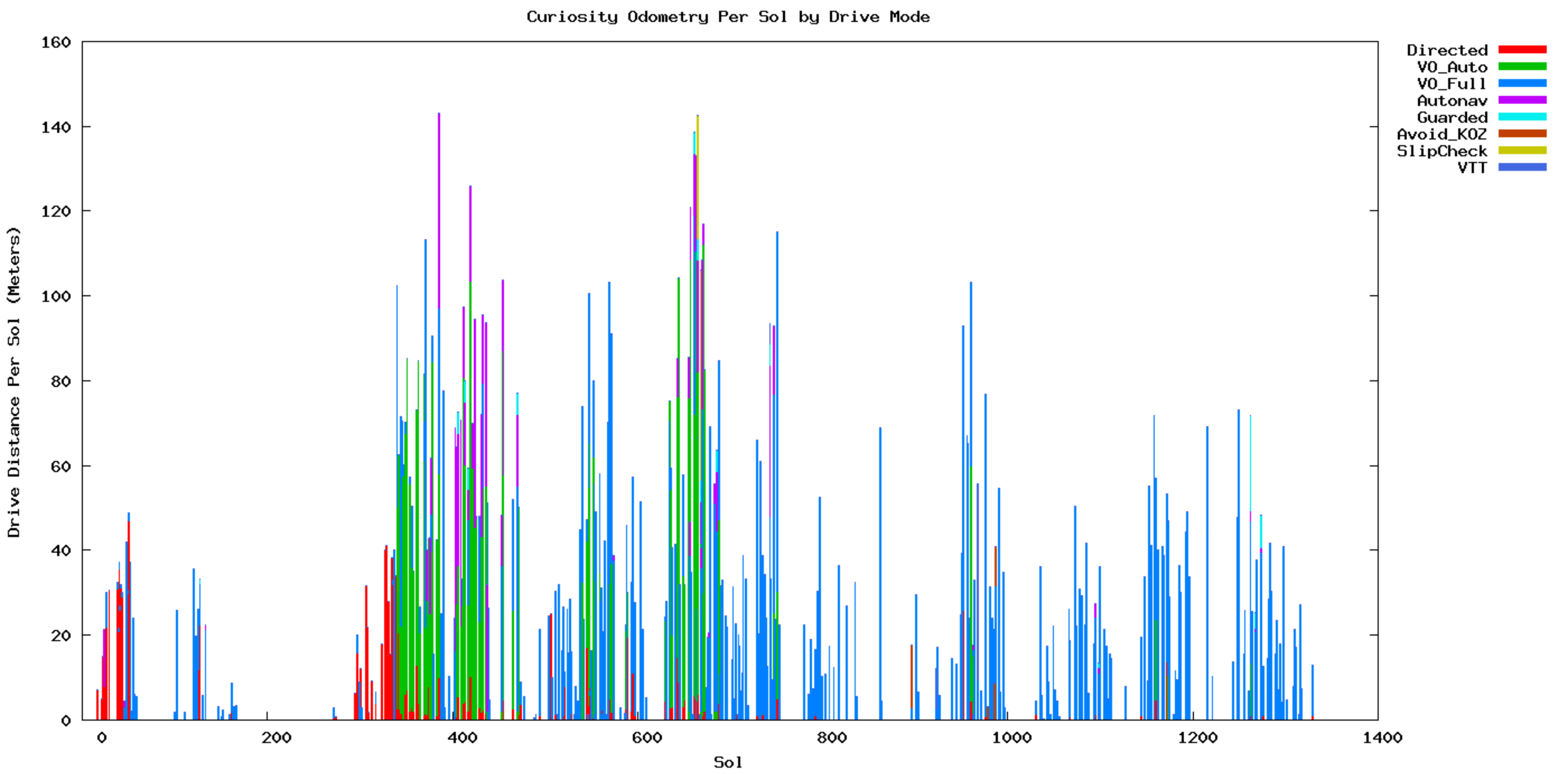
Statistics through sol 1330

Curiosity Odometry Per Sol



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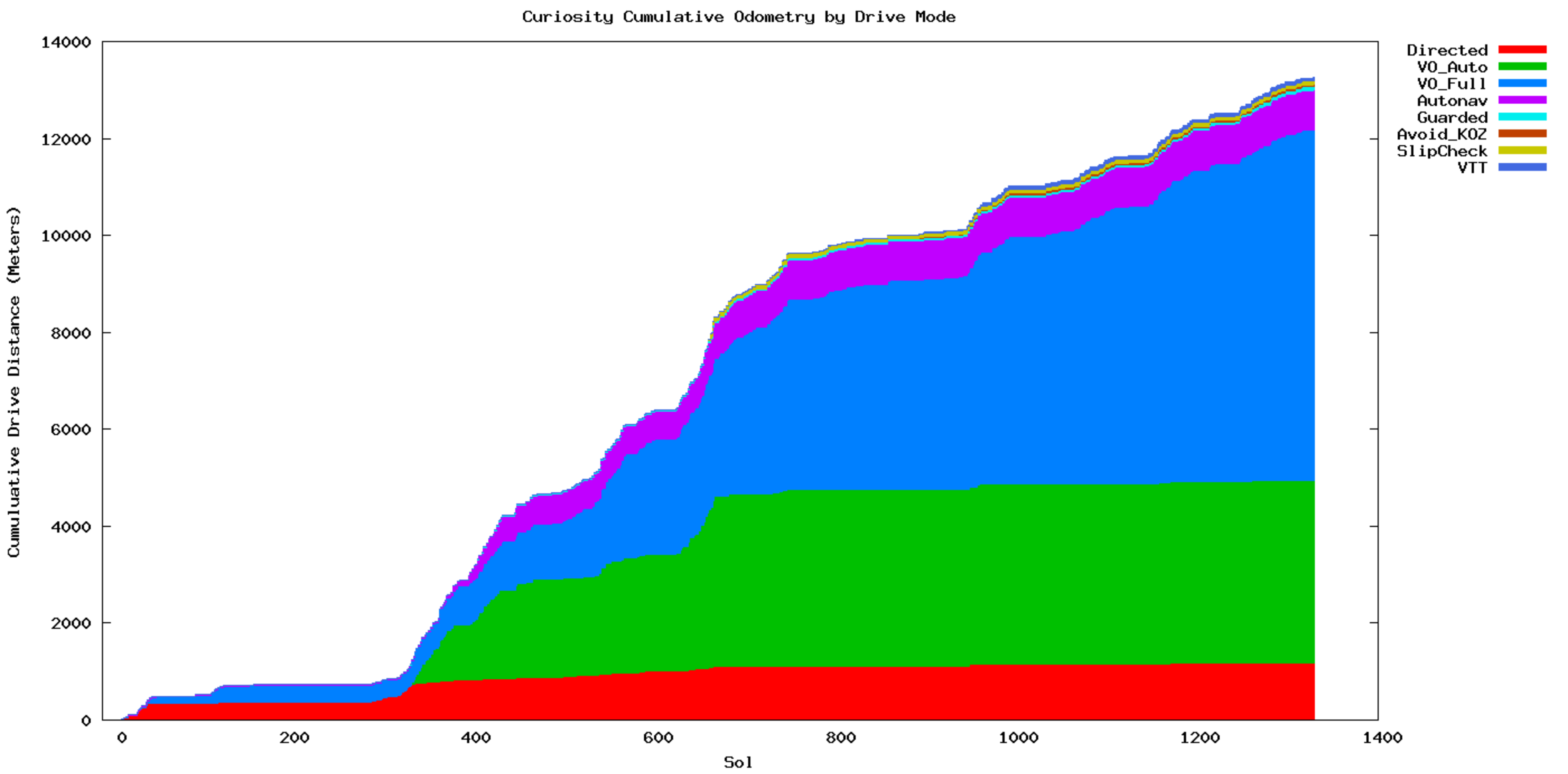
Curiosity Cumulative Odometry



NASA/JPL-Caltech

Flight Rover Specs

	Sojourner	MER	MSL
CPU	80C85	BAE RAD6000	BAE RAD750
MHz	2	20	133
RAM (Mbytes)	0.56	128	512
Non-volatile storage (Mbytes)	0.17	256 flash	4,096 flash
Stereo Pixels processed per step	20	10,000 - 50,000	40,000 - 200,000

Some Sojourner Onboard Capabilities

- Stereo Vision-based Obstacle Detection and Avoidance
  - 5 laser light stripes, processed at 4 locations for 20 samples
- Find Rock
- Thread the Needle Driving
- Fault Recovery

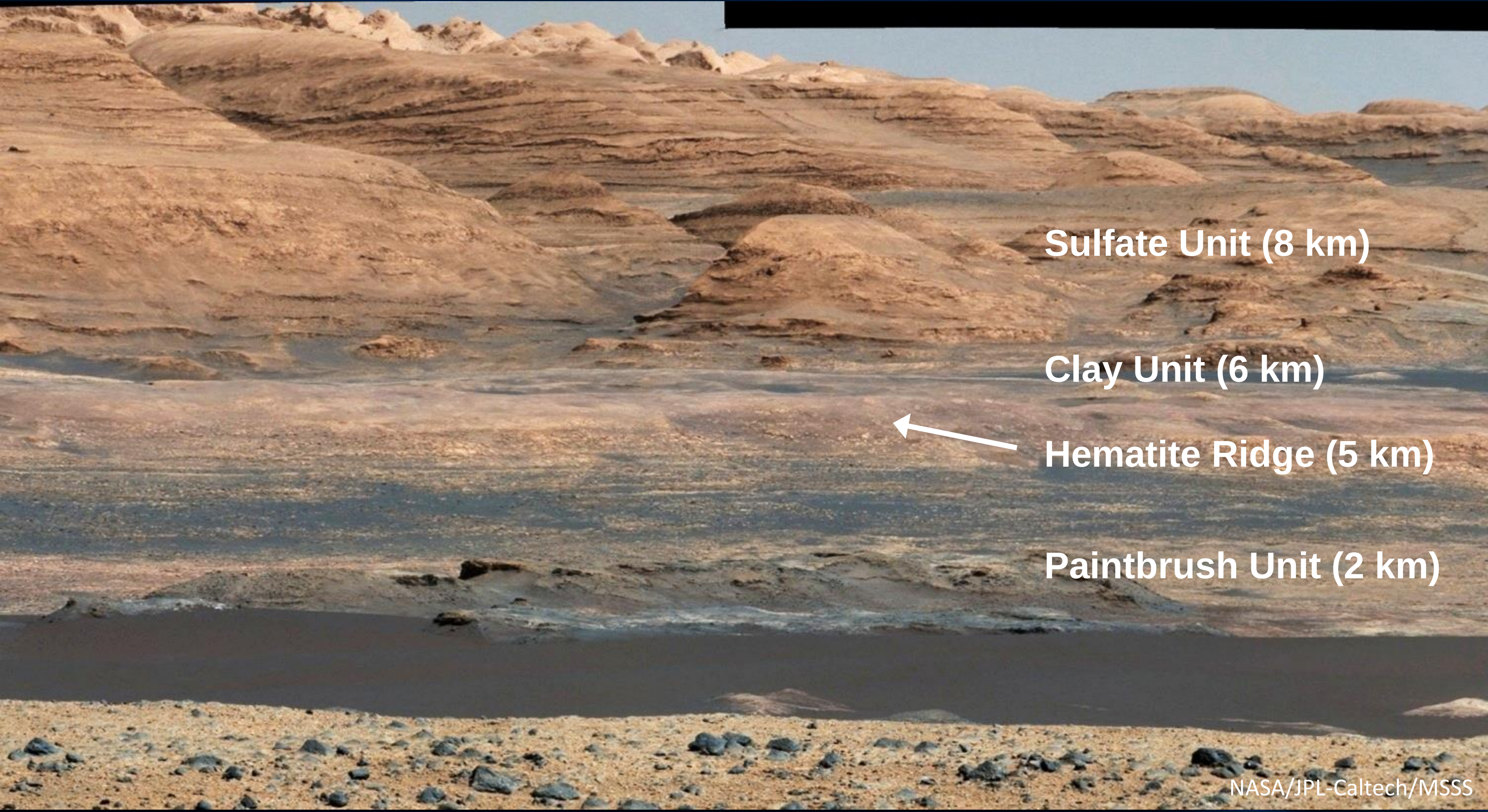
Some MER Onboard Capabilities

- Primary Mission
  - Local Path Selection
  - Dense Stereo Vision for …
  - … Terrain Assessment
  - AutoNav: Hazard Detection and Avoidance
  - Visual Odometry
- Extended Mission Proposal Included Research Infusion
  - Global Path Planner - Field D*
  - Visual Terrain Tracking
  - Autonomous Science, e.g. Dust Devil / Cloud Detection
  - Autonomous Instrument Placement

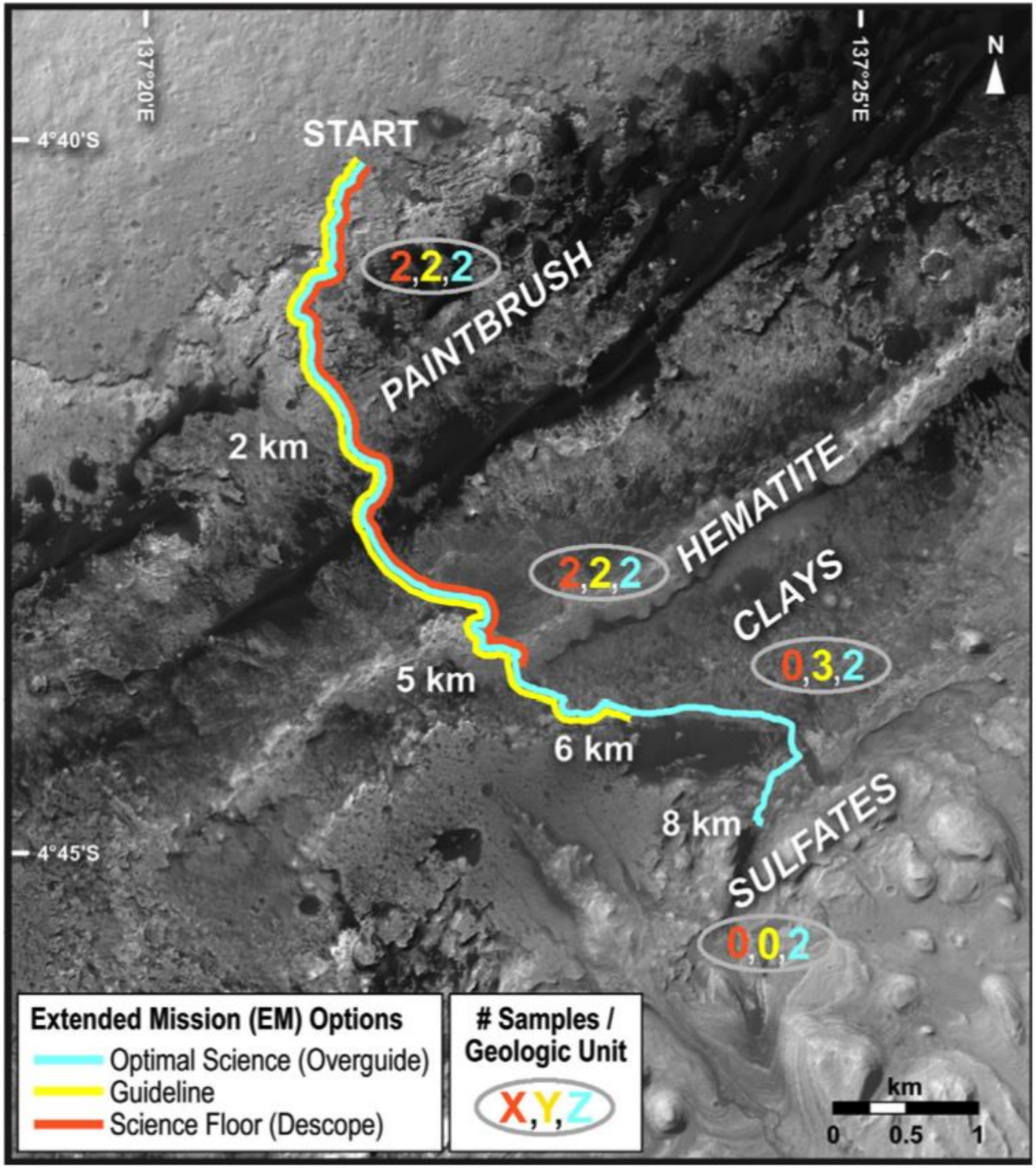
Some MSL Onboard Capabilities

- Primary Mission
  - Local Path Selection and Global Path Planner - Field D*
  - Dense Stereo Vision for …
  - … Terrain Assessment
  - AutoNav: Hazard Detection and Avoidance
  - Visual Odometry
- Post-landing FSW updates
  - Visual Terrain Tracking
  - Autonomous Science – e.g., Dust Devil / Cloud Detection

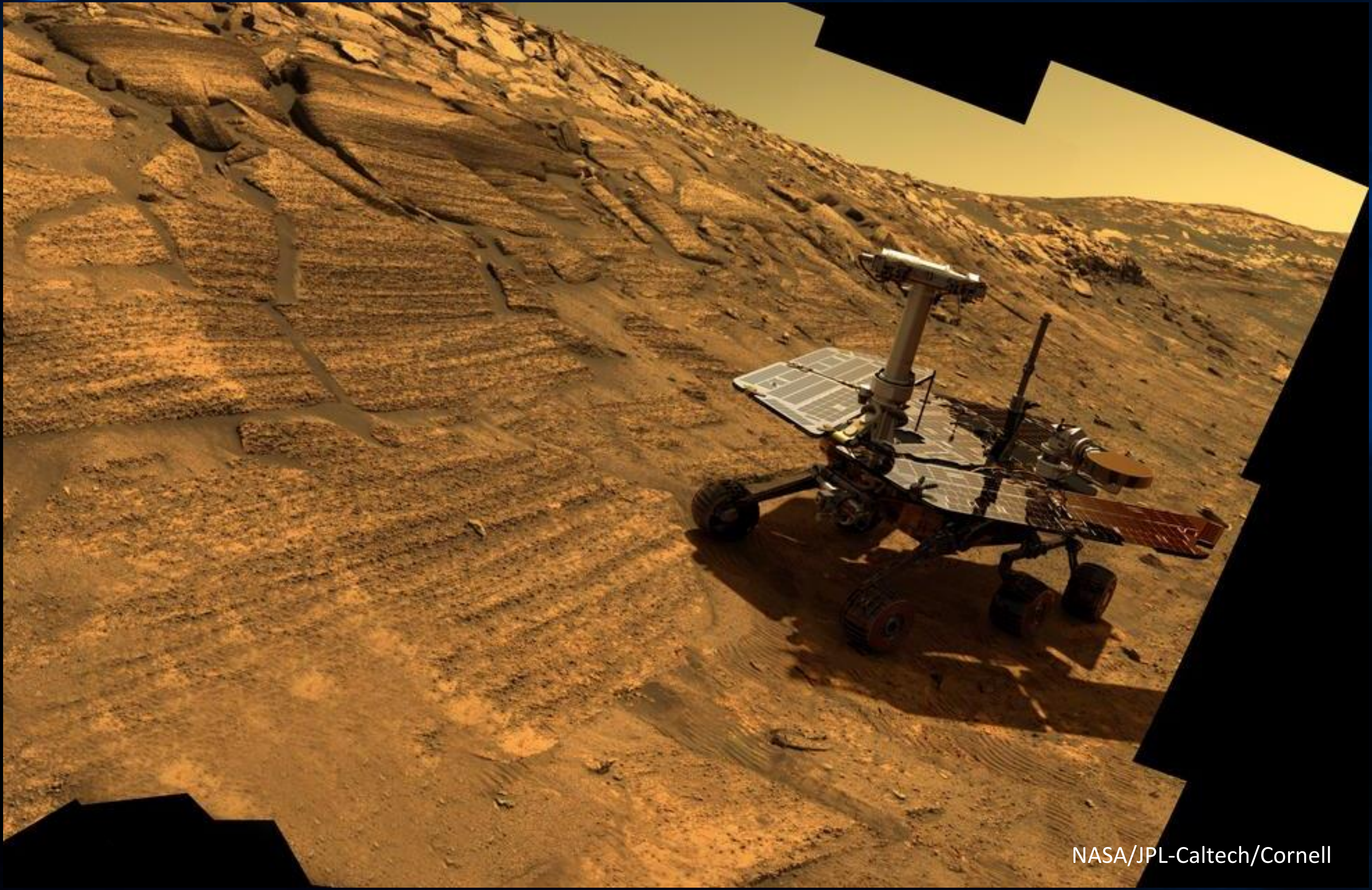
Targets for Exploration



NASA/JPL-Caltech/MSSS


137°20'E
137°25'E
N
4°40'S
4°45'S
START
2,2,2
PAINTBRUSH
2 km
HEMATITE
2,2,2
CLAYS
0,3,2
5 km
6 km
8 km
SULFATES
0,0,2
Extended Mission (EM) Options
Optimal Science (Overguide)
Guideline
Science Floor (Descope)
# Samples / Geologic Unit
X,Y,Z
km
0
0.5
1

Mars Rovers Explore Slopes



NASA/JPL-Caltech/Cornell

And Craters

NASA/JPL/Cornell

And Mountains

NASA/JPL - Caltech/Cornell

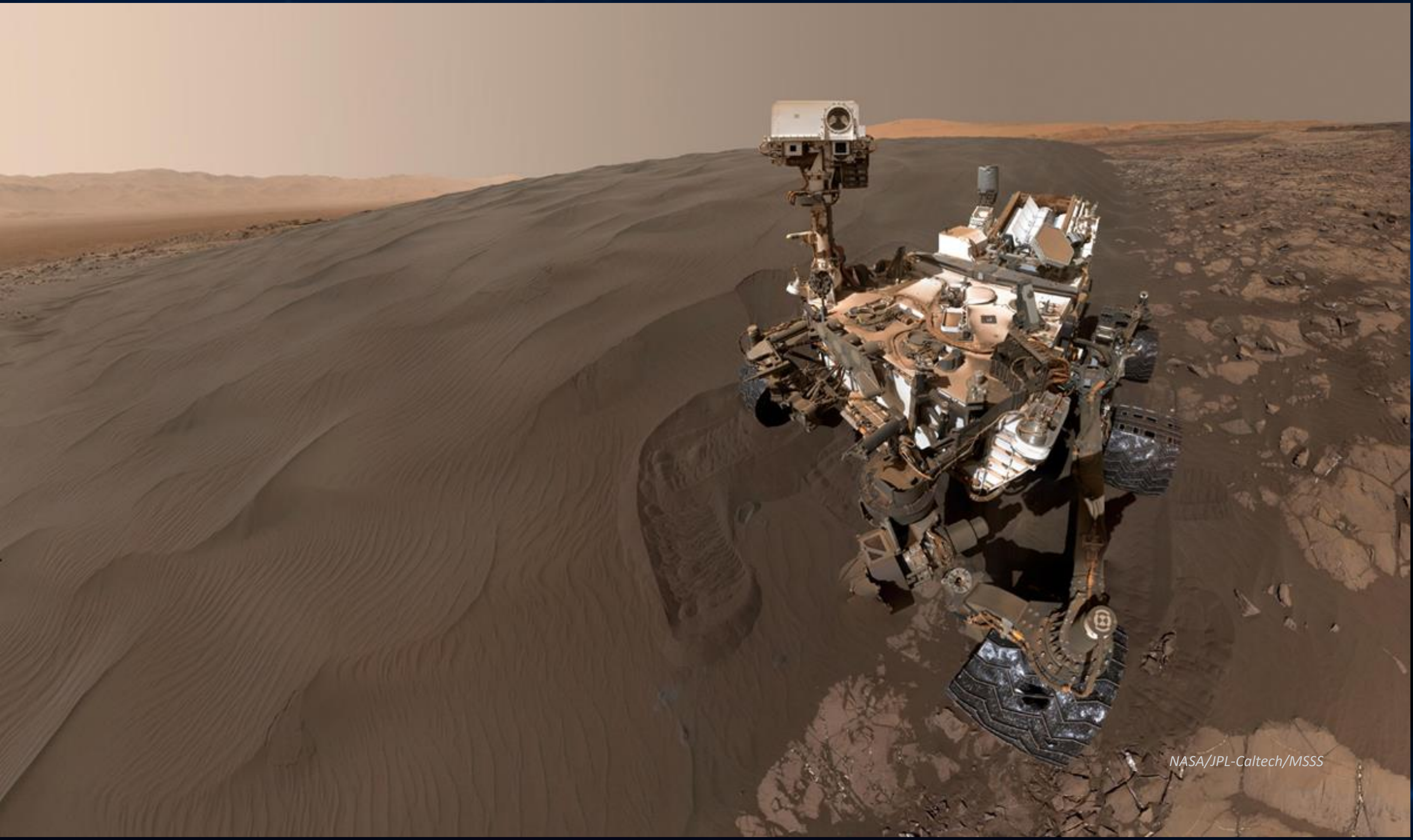
And Discover Buried Treasure

NASA/JPL-Caltech/Cornell

And Overcome Obstacles

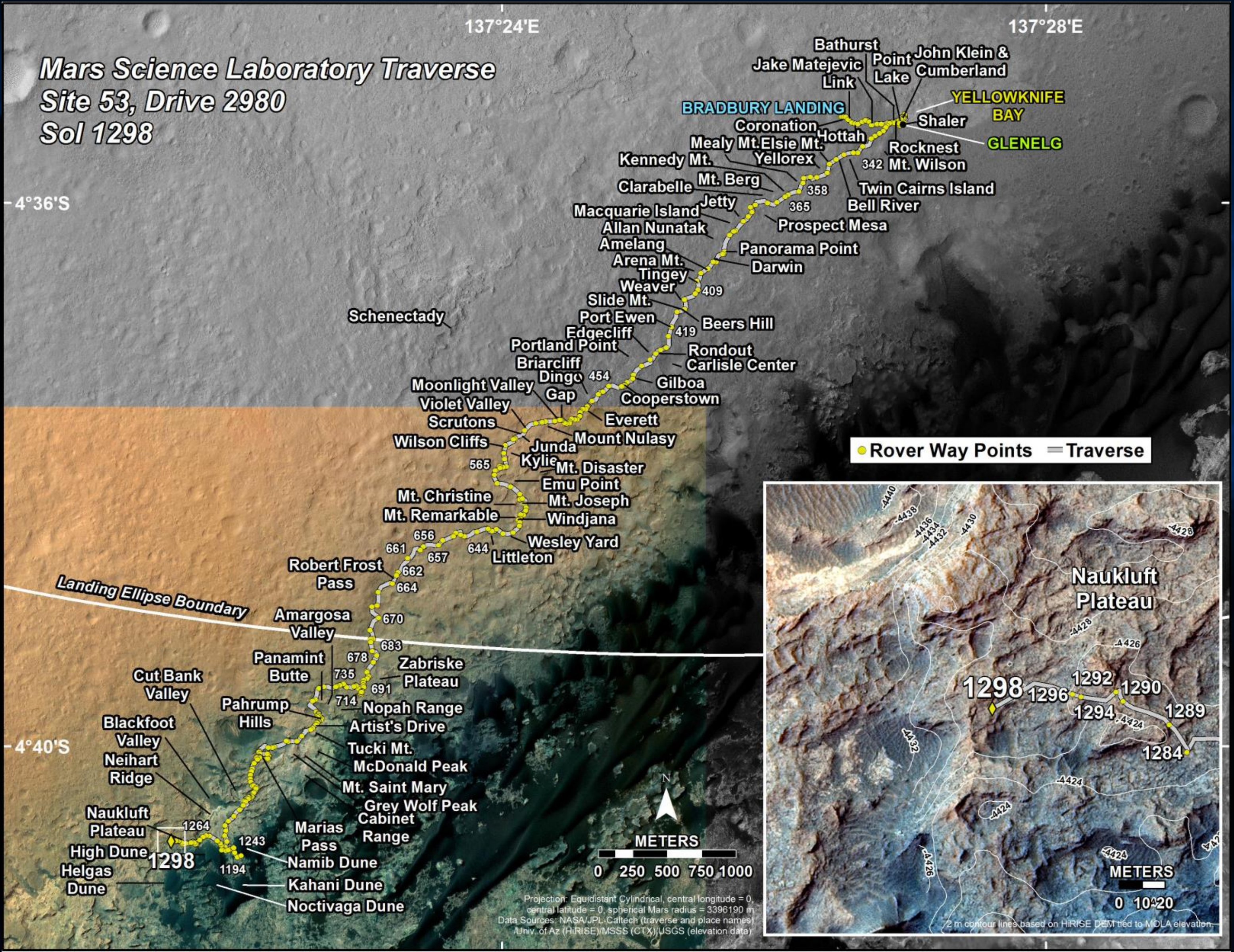
NASA/JPL-Caltech/MSSS

And Explore Novel Terrains



NASA/JPL-Caltech/MSSS

Curiosity Drove 19 km in 5.5 years

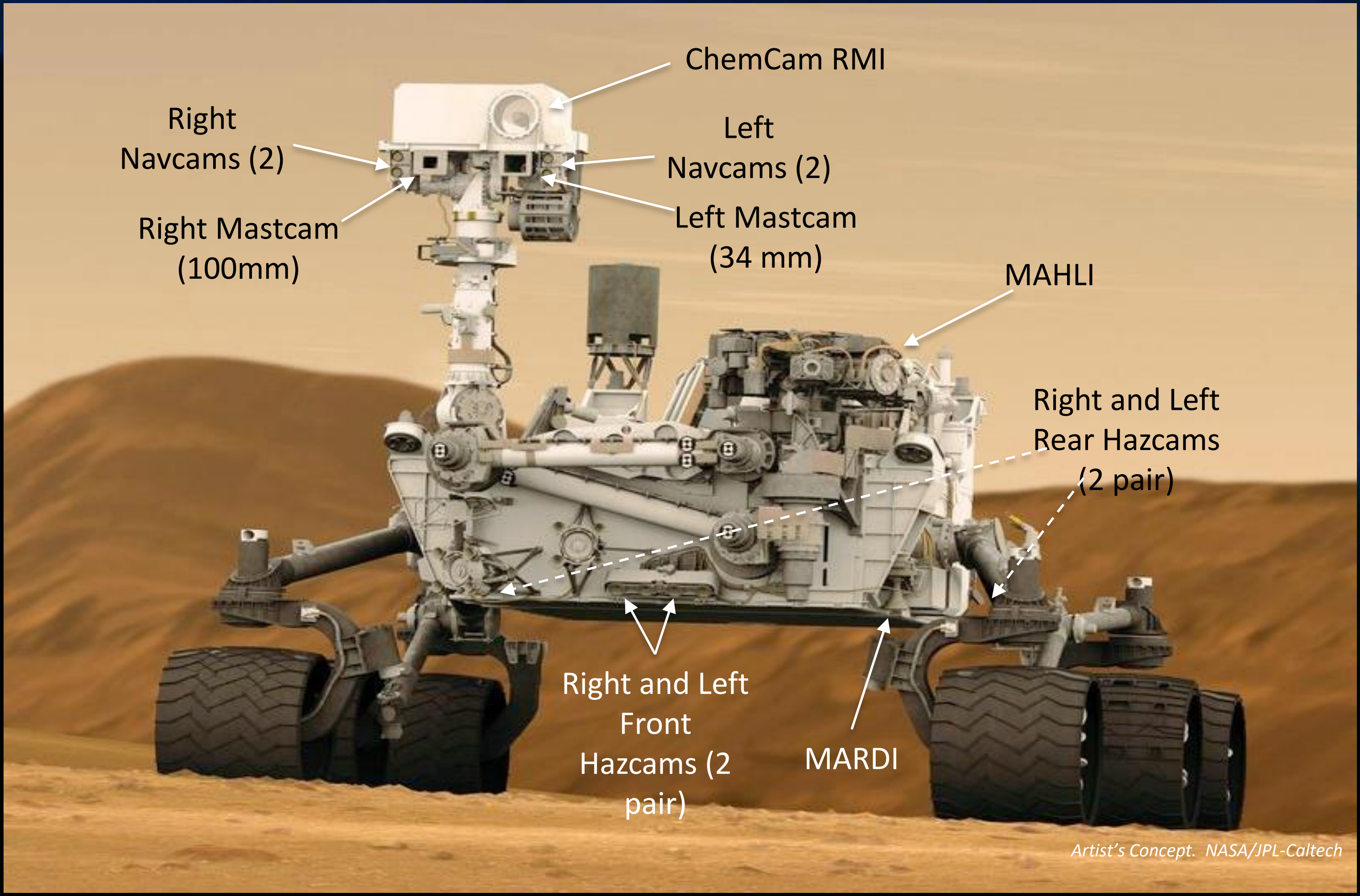


Projection: Equidistant Cylindrical, central longitude = 0, central latitude = 0, spherical Mars radius = 3396190 m
Data Sources: NASA/JPL-Caltech (traverse and place names) /Univ. of Az (HiRISE)/MSSS (CTX)/USGS (elevation data)

2 m contour lines based on HiRISE DEM tied to MOLA elevation.

http://mars.jpl.nasa.gov/msl/multimedia/images/?ImageID=7786

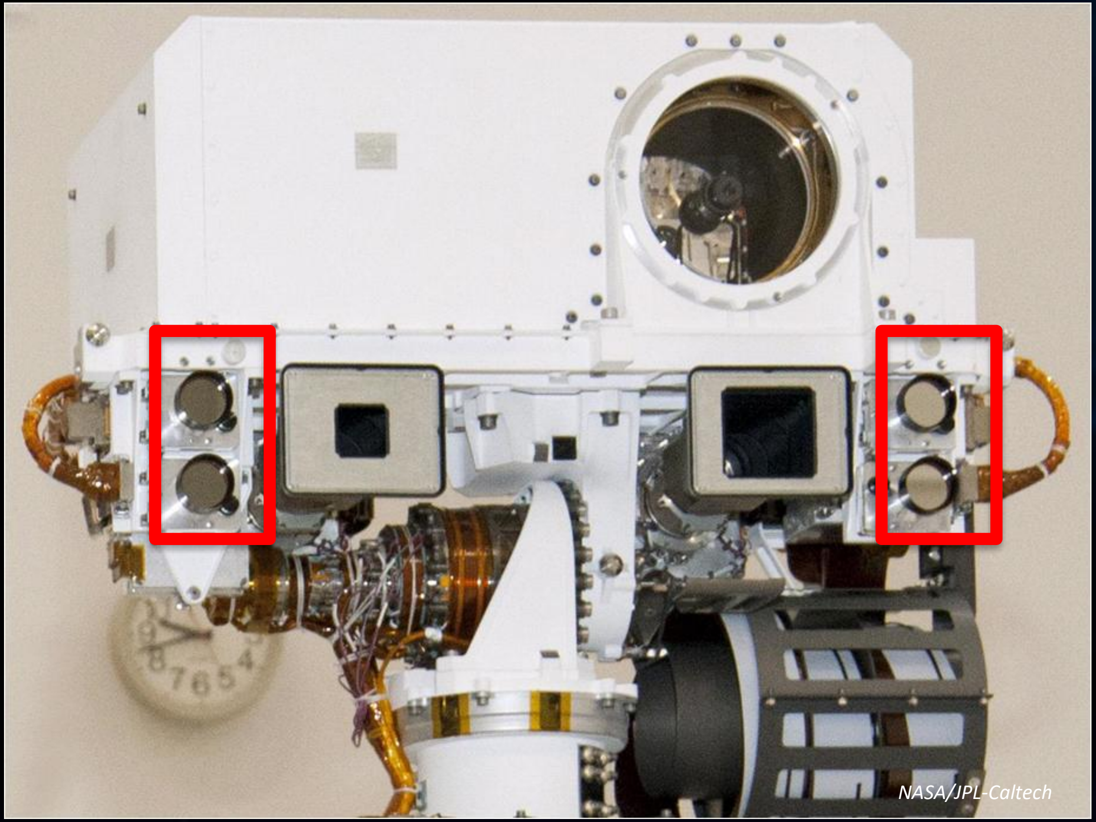
Curiosity has 17 cameras

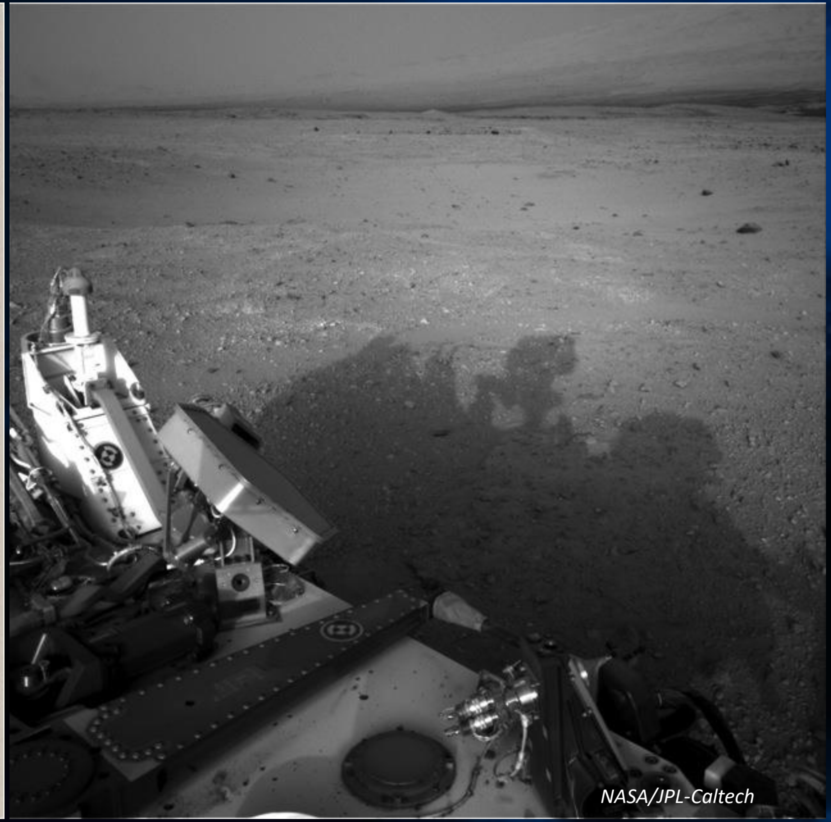


Artist's Concept. NASA/JPL-Caltech

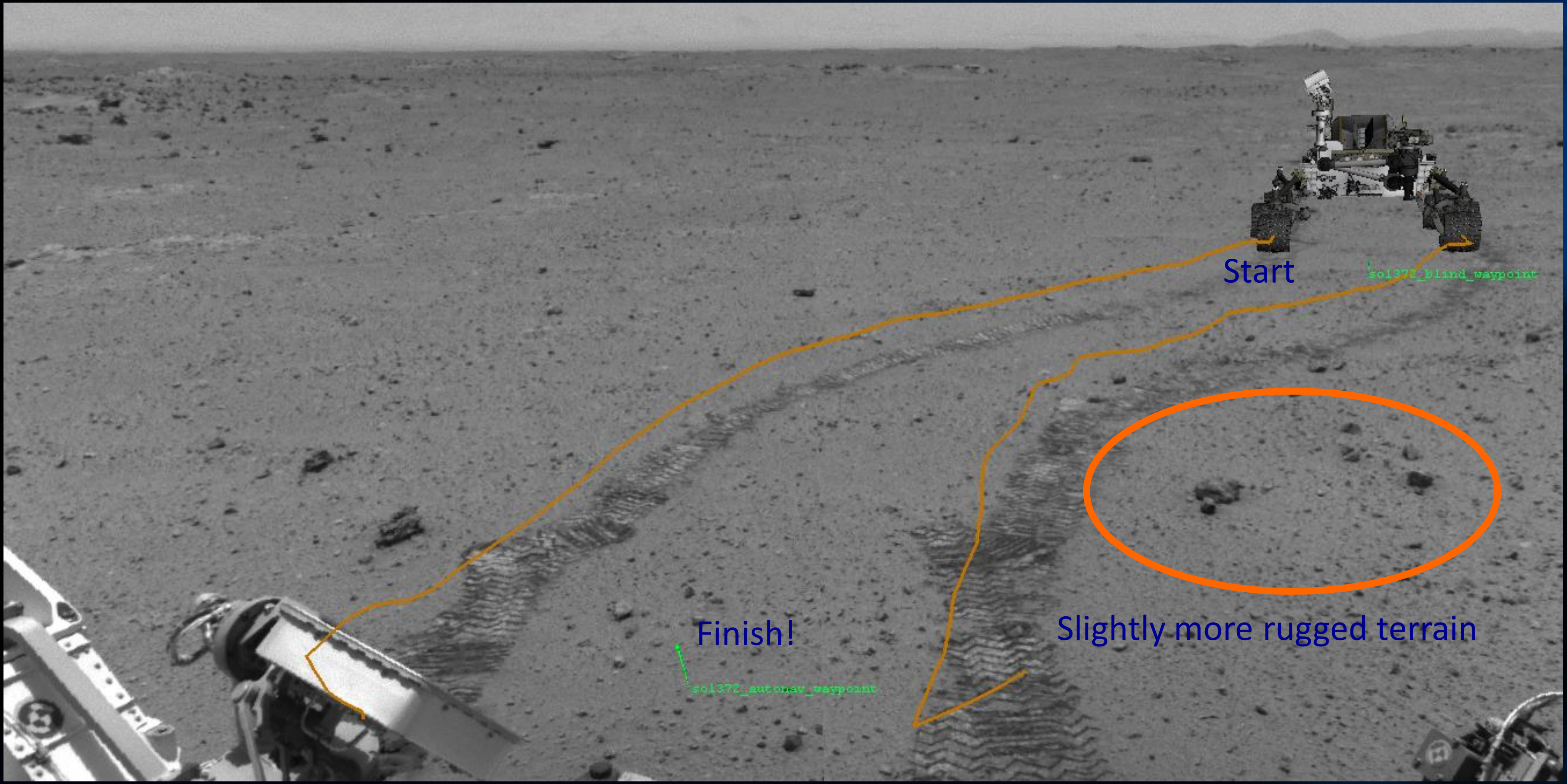
However, only the Hazcams and Navcams are tied into the auto-nav software.

The 45º navigation cameras are almost 7 feet off the ground with 42cm baseline, providing good views over nearby obstacles or hills and into ditches.


NASA/JPL-Caltech

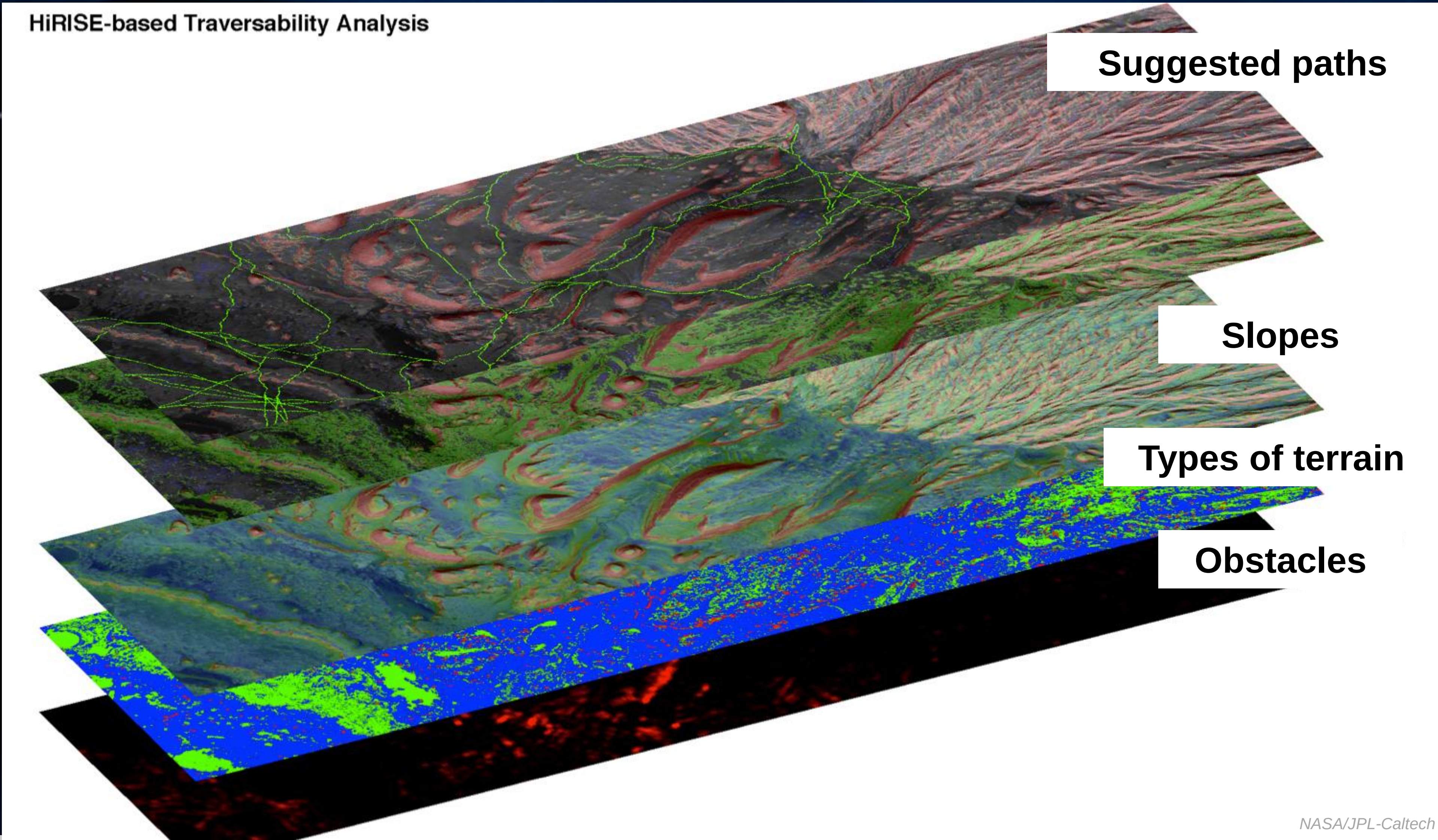

NASA/JPL-Caltech

Wheel tracks after the first auto-nav drive on sol 372 show that Curiosity chose to drive around a little mound of loose rock.



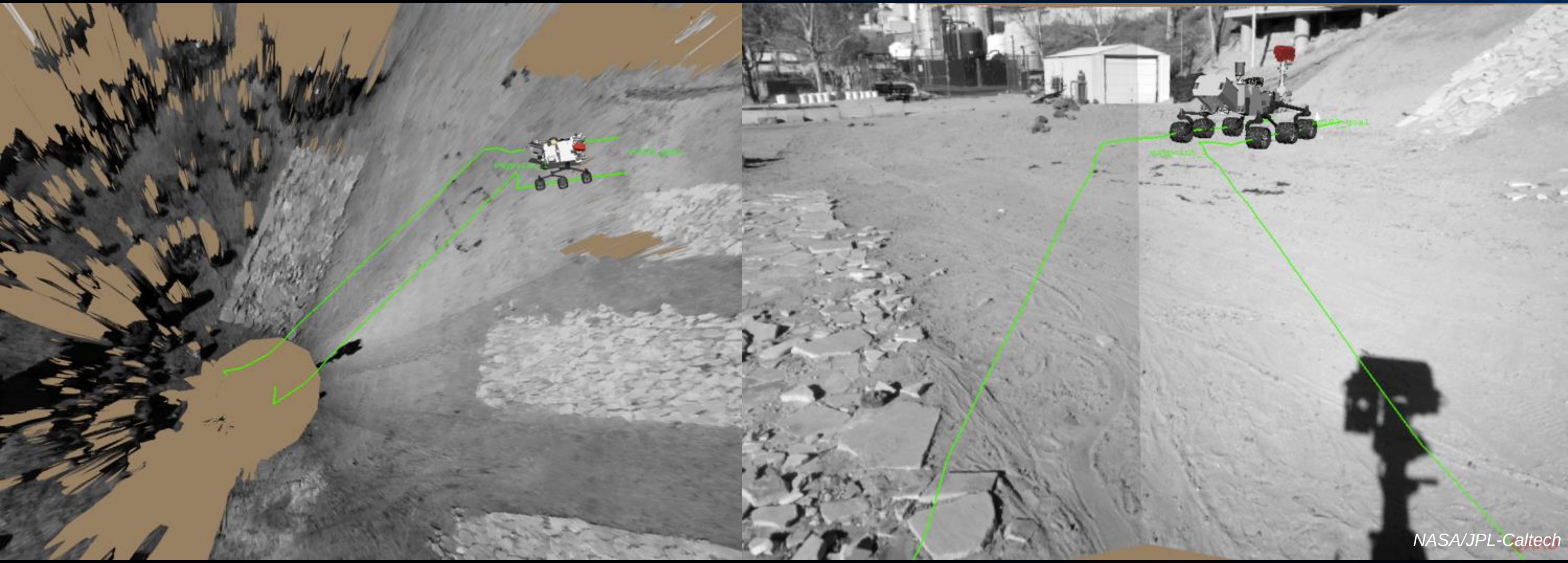
NASA/JPL-Caltech

Data from the Mars Reconnaissance Orbiter helps "see" several kilometers ahead, allowing for long term planning.



NASA/JPL-Caltech

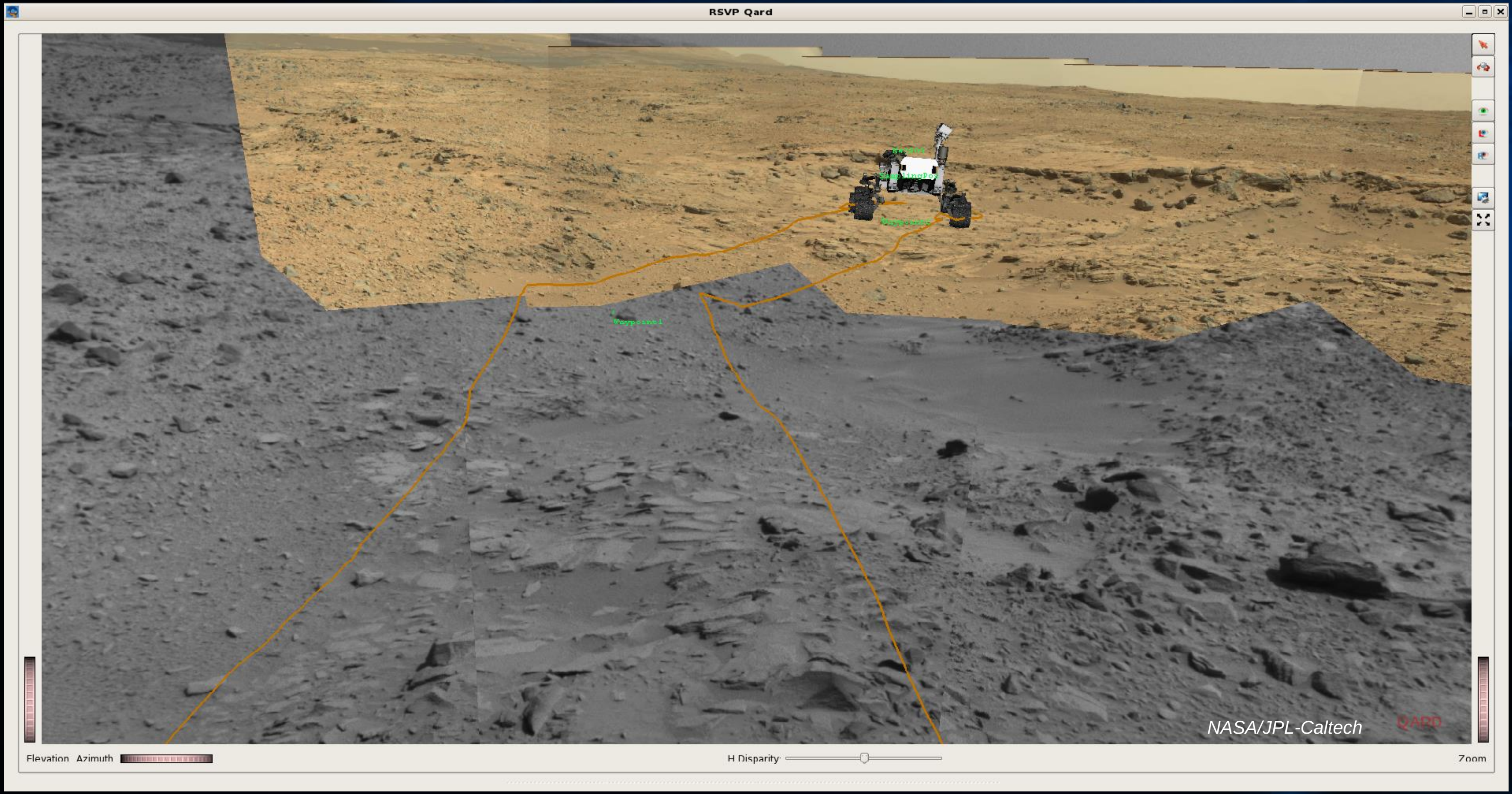
A previous day’s images are fed into the Rover Simulation Visualization Program (RSVP) and 3D meshes are created.



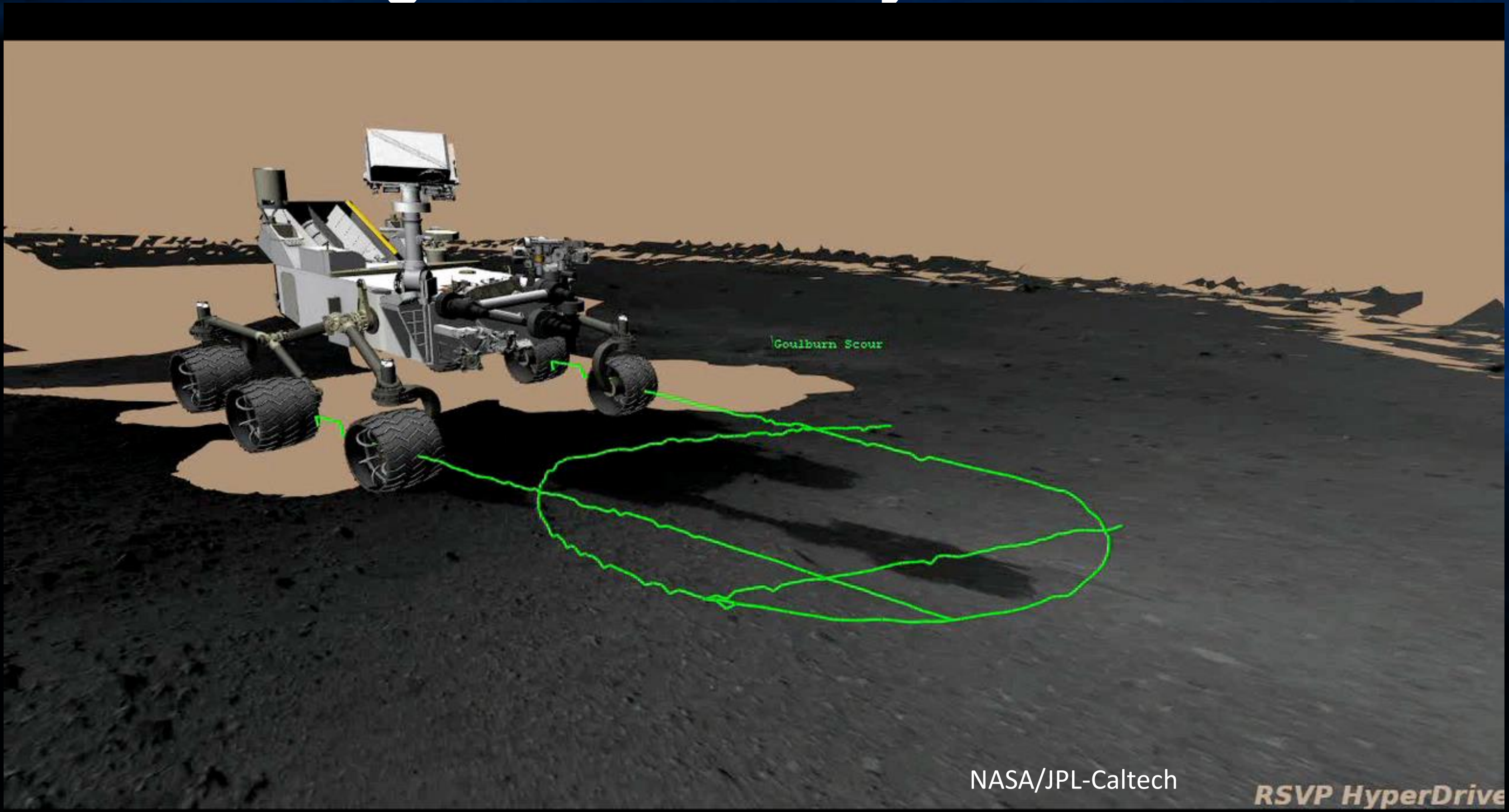
NASA/JPL-Caltech

Rover drivers wear shuttered 3D goggles to view stereo imagery and 3D meshes

The Rover Simulation Visualization Program (RSVP) projects simulated drives into all available images.



For “directed driving,” drivers command the rover to move a certain distance over ground that they know is safe.



NASA/JPL-Caltech

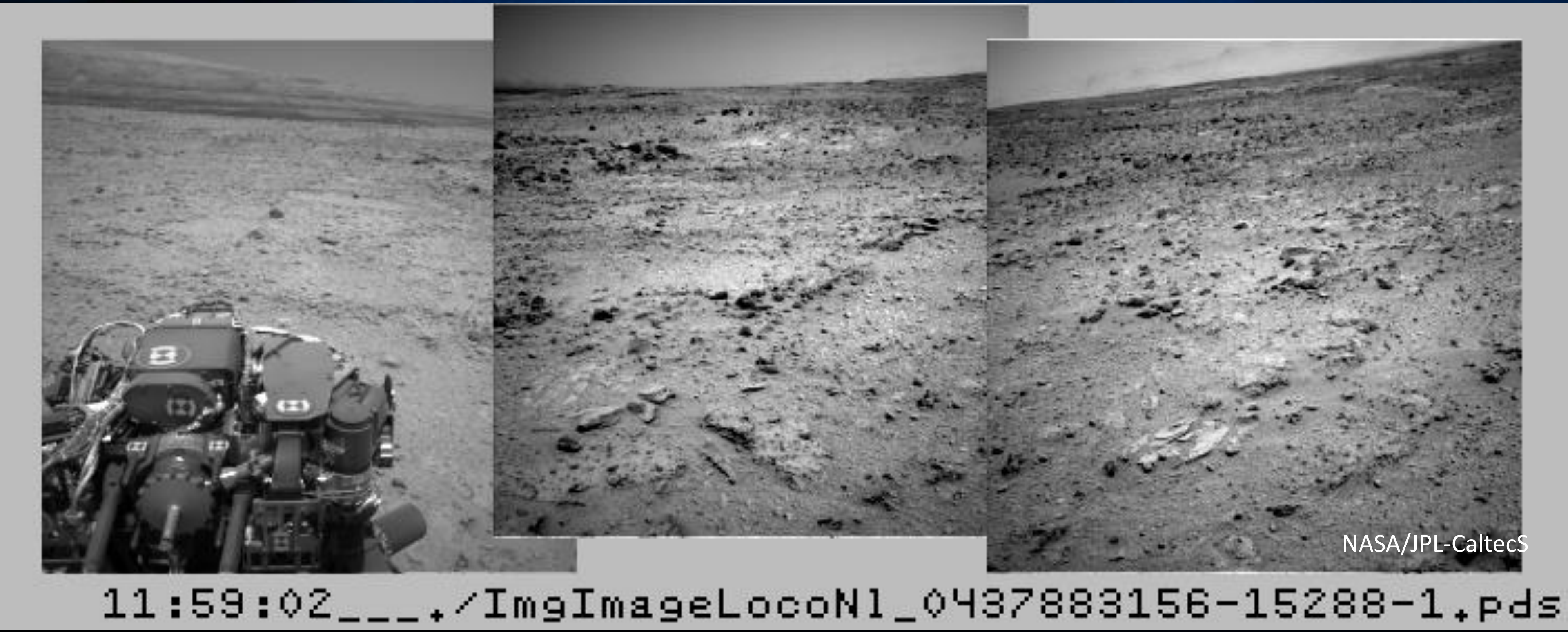
This is the fastest way to drive, because no predictive hazard processing is done, but distance is limited by what people can see. Curiosity will *always* stop the drive if a fault is detected!

Unexpected Challenges!

On sol 455, Curiosity Tried Multi-sol Driving again

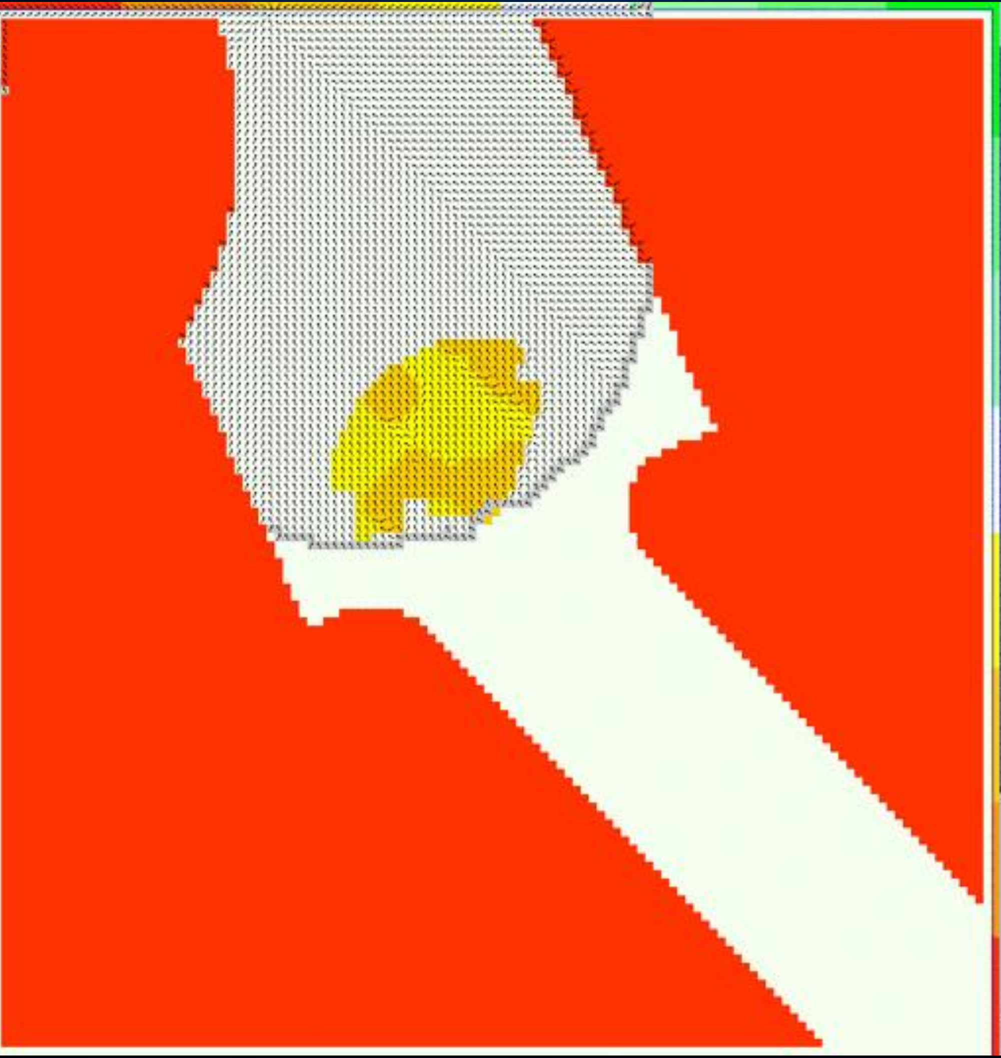
- Multi-sol driving succeeded on sols 435-436!
- But the second try was halted by a drive stall, and interesting D* behavior on the first day, sol 455.

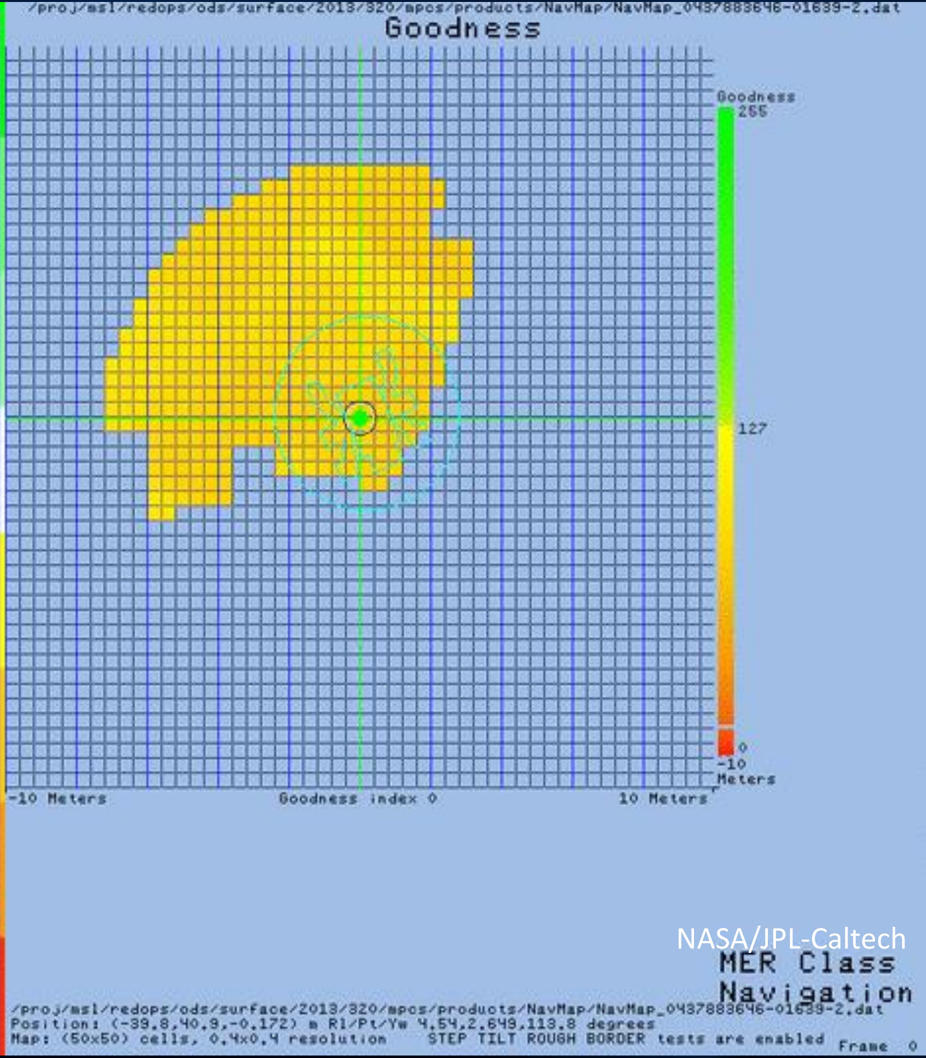
A Rover’s-eye view of the Autonomous Portion of the sol 455 drive



NASA/JPL-CaltecS

Then, boxed in by Keepin Zones, D* tried backtracking!





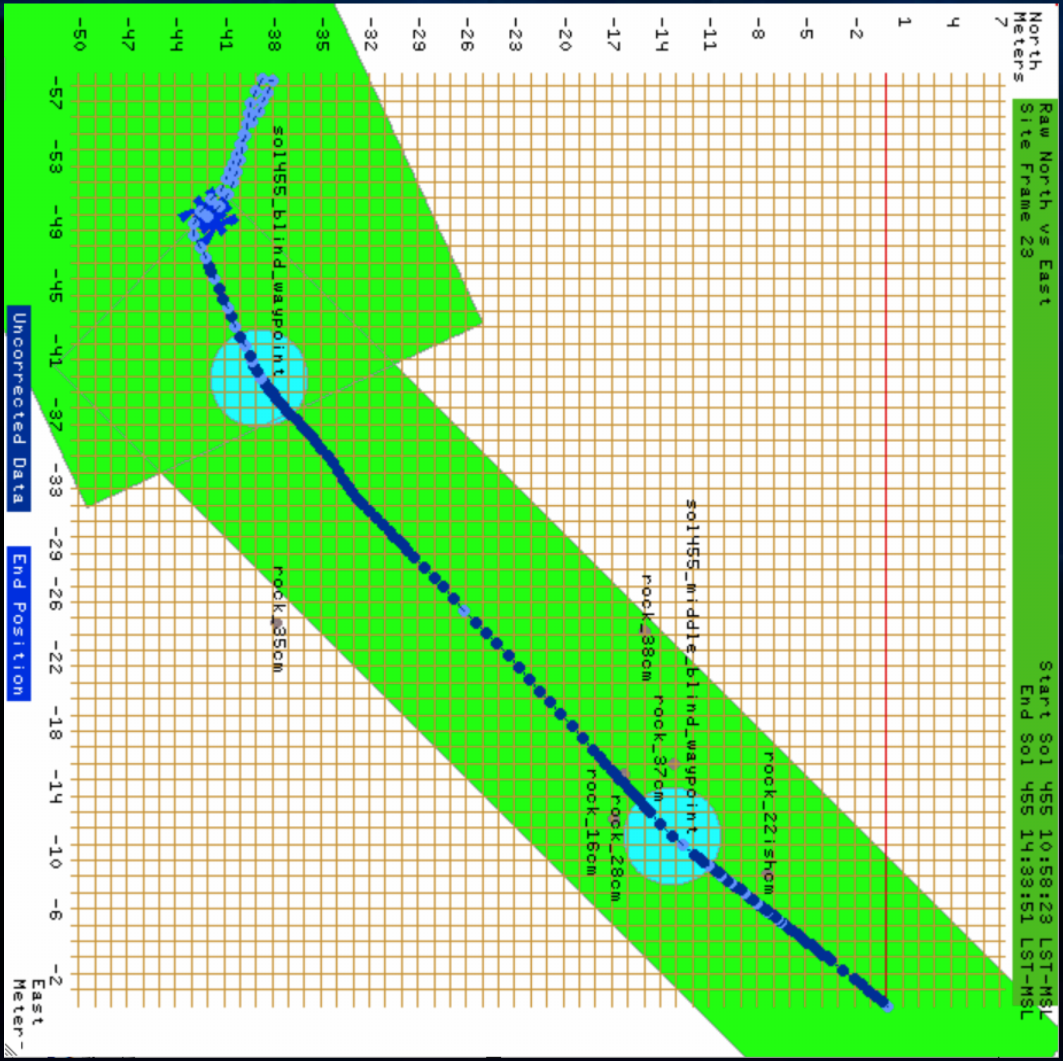
```
/proj/msl/redops/ods/surface/2013/320/mpos/products/NavMap/NavMap_0437883646-01639-2.dat
```

```
/proj/msl/redops/ods/surface/2013/320/mpos/products/NavMap/NavMap_0437883646-01639-2.dat
Position: (-39.8,40.9,-0.172) m Rl/Pt/Yw 4.54,2.649,113.8 degrees
Map: (50x50) cells, 0.4x0.4 resolution    STEP TILT ROUGH BORDER tests are enabled
```

NASA/JPL-Caltech

NASA/JPL-Caltech

On sol 455, Curiosity encountered a small crater and began to drive around it



Small light blue dots represent the imaging steps

NASA/JPL-Caltech

The Road Ahead

NASA/JPL-Caltech/MSSS